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Effects of muscle fatigue on the knee joint- position sense and muscle coactivation of healthy individuals

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To my grandmother,
for teaching me never to give up,
and for all the love and pride.

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List of publications

This doctoral thesis is based on the following scientific publications, referred in the text with Arabic numbers:

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Table of Contents

Acknowledgments	iii
List of Publications	v
Index of Tables	ix
Index of Figures	xi
Index of Equations	xiii
Abstract	xv
Resumo	xvii
List of Abbreviations and Symbols	xix
Chapter 1. General Introduction	1
Chapter 2. The effect of muscle fatigue on the knee proprioception: a systematic review	7
Chapter 3. Normative values and accuracy-influencing factors for knee joint-position sense assessments: a cross-sectional study	69
Chapter 4. Is the knee joint-position sense affected by different concentric or eccentric fatigue protocols of the quadriceps or hamstrings? A randomized controlled crossover trial	99
Chapter 5. Muscle coactivation during knee joint-position sense assessments: the effect of muscle fatigue and implications for the magnitude of errors and directional bias	131
Chapter 6. General Discussion	165
Chapter 7. General Conclusions	173
Chapter 8. References	176

Index of Tables

Chapter 2	Table 1. Quality assessment of the included studies according to the Methodological Index for Non-Randomized Studies (MINORS) (Slim et al., 2003).	23
	Table 2. Summary table of the included studies in the systematic review with main findings.	26
Chapter 3	Table 1. Characterization of the total sample and by sex group, regarding age, body mass, height, and BMI.	79
	Table 2. Normative values (AAE) and sex (male vs. female) and dominance (dominant vs. non-dominant limb) comparisons across the different knee JPS tests (in degrees).	80
	Table 3. Comparison of AAE between target angles (20° vs. 45°) across the different JPS tests (in degrees).	83
Chapter 4	Table 1. Intra- and intergroup comparisons regarding the AAE (in degrees) during knee JPS tests.	113
	Table 2. Torque and power results between the first (Beg.) and last (End) group of three contractions of the four muscle fatigue protocols.	114
	Table 3. EMG results between the first (Beg.) and last (End) group of three consecutive contractions of the four muscle fatigue protocols.	116
Chapter 5	Table 1. Comparisons of coactivations and mean activations of VL and BF between the participants presenting lower and more errors (magnitude of errors comparison) and those failing the target angle into the extension or flexion direction (directional bias), before and after fatigue.	145

Table 2. Comparisons of coactivations and mean activations of VL and BF between the participants presenting lower and more errors (magnitude of errors comparison) and those failing the target angle into the extension or flexion direction (directional bias), before and after fatigue.

147

Index of Figures

Chapter 2	Figure 1. PRISMA flow diagram of the literature selection process.	15
	Figure 2. Traffic-light plot according to the Cochrane risk-of-bias (RoB2) tool version 2 (Sterne et al., 2019) D1: (D1: Randomisation process; D2: Deviations from the intended interventions; D3: Missing outcome data; D4: Measurement of the outcome; D5: Selection of the reported results).	16
	Figure 3. Summary plot according to the Cochrane risk-of-bias (RoB2) tool version 2 (Sterne et al., 2019).	17
Chapter 3	Figure 1. Illustration of the knee JPS tests in the sitting position: (A) initial position for the concentric repositioning test (to extension); and (B) initial position for the eccentric repositioning test (to flexion); (C) describes the leg positioned at the target angle of 20° and (D) at 45° of knee flexion.	75
	Figure 2. Illustration of the knee JPS tests in the prone position: (A) initial position for the concentric repositioning test (to flexion); (B) initial position for the eccentric repositioning test (to extension); (C) describes the leg positioned at the target angle of 20° and (D) at 45° of knee flexion.	76
	Figure 3. Illustration of the knee JPS assessments in the standing position, demonstrating the unilateral squat: (A) initial position; (B) describes the leg positioned at the target angle of 20°; and (C) at 45° of knee flexion.	77
	Figure 4. Illustration of the knee JPS assessments in the standing position, demonstrating the bilateral squat: (A) initial position; (B) describes the leg positioned at the target angle of 20°; and (C) at 45° of knee flexion.	77

Chapter 4	Figure 1. JPS procedures for the SIT_CC test: (A) describes the starting position (90° of knee flexion), and (B) the leg positioned at the target angle (45° of knee flexion).	107
	Figure 2. JPS procedures for the SIT_ECC test: (A) describes the starting position (full knee extension), and (B) the leg positioned at the target angle (45° of knee flexion).	108
	Figure 3. JPS procedures for the PRONE_CC test: (A) describes the starting position (full knee extension), and (B) the leg positioned at the target angle (45° of knee flexion).	108
	Figure 4. JPS procedures for the PRONE_ECC test: (A) describes the starting position (90° of knee flexion), and (B) the leg positioned at the target angle (45° of knee flexion).	108
	Figure 5. CONSORT flow diagram for crossover trials.	111
Chapter 5	Figure 1. JPS procedures for the SIT_CC test: (A) describes the starting position (90° of knee flexion), and (B) the leg positioned at the target angle (45° of knee flexion).	137
	Figure 2. JPS procedures for the SIT_ECC test: (A) describes the starting position (full knee extension), and (B) the leg positioned at the target angle (45° of knee flexion).	137
	Figure 3. Coactivation results in the assessed JPS tests, before (PRE) and after (POST) inducing fatigue on the quadriceps (QD_CC) and hamstrings (HS_CC); * significantly different from PRE.	142
	Figure 4. <i>Vastus lateralis</i> (VL) and <i>biceps femoris</i> (BF) mean EMG activation results in the assessed JPS tests, before (PRE) and after (POST) inducing fatigue on the quadriceps (QD_CC) and hamstrings (HS_CC); * significantly different from PRE.	143

Index of Equations

Chapter 5	Equation 1	$CI = 2 \times \frac{\text{EMG antagonist}}{(\text{EMG Agonist} + \text{EMG Antagonist})} \times 100$	140
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Abstract

This thesis investigated the effect of muscle fatigue (MF) on the knee joint position sense (KJPS) and muscle coactivation of healthy individuals. In addition, normative values for different KJPS assessments were provided, and the influence of protocol-related and individual factors was examined. To accomplish this, four studies were conducted: (i) a systematic review summarizing the evidence on the impact of MF on the knee proprioception; (ii) a cross-sectional study that aimed to provide normative values for KJPS assessments, covering different parameters that could enhance repositioning accuracy (test position, type of repositioning, and target angles), as well as the influence of individual factors (sex and dominance); (iii) a randomized controlled trial investigating the effects of different localized MF protocols on the KJPS; and (iv) a quasi-experimental study describing muscle coactivation patterns during JPS assessments before and after inducing MF. The results showed that: (i) MF negatively affects knee proprioception in both trained and untrained individuals, regardless of whether fatigue is induced locally or generally; (ii) KJPS assessments performed in standing and sitting positions result in better repositioning accuracy; the type of repositioning (concentric/eccentric) does not appear to influence repositioning errors; proprioceptive acuity is greater at extreme angles when KJPS is assessed in non-weight-bearing, and greater at intermediate angles in weight-bearing assessments; and sex and dominance do not seem to have an effect; (iii) isolated concentric and eccentric MF protocols involving the quadriceps and hamstrings negatively impact KJPS; and (iv) coactivation between knee extensors and flexors is high during JPS tests, possibly as a strategy to maintain accuracy, with MF leading to reduced coactivation. These studies confirm a negative effect of MF on the KJPS and muscle coactivation of healthy individuals, which may contribute to joint instability and increased injury risk.

Resumo

Esta tese explorou o efeito da fadiga muscular (MF) na sensação de posição articular do joelho (KJPS) e na coativação muscular de indivíduos saudáveis. Além disso, foram fornecidos valores normativos em diferentes avaliações da KJPS, e estudado o impacto de fatores relacionados com o protocolo de avaliação e de fatores individuais. Para tal, foram efetuados quatro estudos: (i) uma revisão sistemática, que sumarizou a evidência acerca do efeito da MF na proprioção do joelho; (ii) um estudo transversal que objetivou fornecer valores normativos em avaliações da KJPS cobrindo diferentes parâmetros de avaliação que poderiam levar a uma precisão superior no reposicionamento (posição de teste, tipo de reposicionamento, e ângulos-alvo), assim como a influência dos fatores individuais (sexo e dominância); (iii) um estudo randomizado controlado que investigou os efeitos de diferentes protocolos de MF localizados na KJPS; e (iv) um estudo quase-experimental que visou descrever os padrões de coativação muscular durante avaliações da KJPS, antes e após a indução de MF. Os resultados destes estudos demonstraram: (i) que a MF afeta negativamente a proprioção do joelho de indivíduos treinados e não-treinados, seja ela induzida de forma localizada ou generalizada; (ii) que avaliações da KJPS em pé e sentado levam a precisões superiores no reposicionamento; que o tipo de reposicionamento (concêntrico/excêntrico) parece não afetar os erros de reposicionamento; que a acuidade é superior em ângulos extremos quando a KJPS é avaliada em cadeia cinética aberta, e superior em amplitudes intermédias em avaliações em cadeia cinética fechada; e que o sexo e a dominância parecem não ter influência; (iii) protocolos isolados de MF concêntricos e excêntricos envolvendo o quadríceps e os isquiotibiais afetam negativamente a KJPS; e (iv) a coativação muscular entre os extensores e flexores do joelho é alta em testes de KJPS, o que pode ser uma estratégia para manter a precisão, sendo que a MF leva a uma diminuição desta coativação. Estes estudos confirmam assim um efeito negativo da MF na KJPS e na coativação muscular de indivíduos saudáveis, podendo contribuir para a instabilidade da articulação e para um risco aumentado de lesão.

List of Abbreviations and Symbols

AAE	Absolute angular errors
BF	<i>Biceps femoris</i>
BMI	Body mass index
BW	Body weight
CG	Control group
CI	Coactivation index
CKC	Closed kinetic chain
CNS	Central nervous system
DOM	Dominant limb
DOMS	Delayed-onset muscle soreness
EG	Experimental group
EMG	Electromyography
F	Female
HR	Heart rate
HS_CC	Concentric fatigue protocol of the hamstrings
HS_ECC	Eccentric fatigue protocol of the hamstrings
ICC	Intraclass correlation coefficient
IPAQ	International Physical Activity Questionnaire
IQR	Interquartile range
JPS	Joint-position sense
KF	Knee flexion
KJPS	Knee joint-position sense

M	Male
Mdn	Median
MINORS	Methodological Index for Non-Randomized Studies
MVIC	Maximum voluntary isometric contraction
NDOM	Non-dominant limb
OKC	Open kinetic chain
POST	Assessments post-fatigue
PRE	Assessments pre-fatigue
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analysis
PRONE_CC	Concentric repositioning test in the prone position
PRONE_ECC	Eccentric repositioning test in the prone position
PROSPERO	International Prospective Register of Systematic Reviews
PT	Peak torque
<i>r</i>	Effect size
RAE	Relative angular errors
RMS	Root mean square
RoB2	Cochrane risk-of-bias tool version 2
ROM	Range of motion
RPOS	Repositioning period
SIT_CC	Concentric repositioning test in the sitting position
SIT_ECC	Eccentric repositioning test in the sitting position
STABLE	Isometric contraction period between repositioning attempts

STROBE	Strengthening the Reporting of Observational Studies in Epidemiology
TREND	Transparent Reporting of Evaluations with Nonrandomized Designs
TTDPM	Threshold to detect passive motion
VAE	Variable angular errors
VL	<i>Vastus lateralis</i>

Chapter 1

General Introduction

Proprioception was first defined by Charles Sherrington in 1906 as the perception of joint and body motion, as well as the body or body segments' position in space (Sherrington, 1920). In general, three subcomponents of proprioception are distinguished: (i) the joint-position sense (JPS), which dictates the ability to memorize a joint angle, and to reproduce it actively or passively, without relying on visual information (Riemann et al., 2002); (ii) kinesthesia, also designated by motion sense, determined as the ability to detect slow passive motion (Lephart et al., 1997; Riemann et al., 2002); and (iii) force sense, which refers to the capacity of reproducing a given magnitude of force or torque (Riemann et al., 2002).

Proprioception of the knee is mainly ensured by muscle (Muscle Spindles and Golgi Tendon Organs) (Craig & Rollman, 1999; Gandevia & Burke, 1992; Lephart et al., 1998) and joint mechanoreceptors (Ruffini terminations, Golgi terminations, Paccini terminations, and free terminations), while cutaneous receptors are argued to have just a minimal contribution (Lephart et al., 1998). According to Proske (2023), muscle spindles are muscle mechanoreceptors capable of providing positional information across a full joint range of motion (ROM), despite being particularly active in intermediate ranges (Docherty et al., 1998), especially between 40°-80° of knee flexion (Olsson et al., 2004). Joint mechanoreceptors are more active at extreme ranges (Proske, 2023; Riemann & Lephart, 2002).

Muscle fatigue describes a condition in which the skeletal muscle fails to generate or sustain force and power due to peripheral and/or central factors (Gandevia, 2001; Rampichini et al., 2020). Peripherally, the decline in muscle function stems from energy substrate depletion, the accumulation of metabolic products, such as lactate, inorganic phosphates, hydrogen ions, and reactive oxygen species, and impaired calcium handling, which altogether are responsible for the decline in the actin and myosin cross-bridges formation, thus reducing the contractile force (Boyas & Guével, 2011; Tornero-Aguilera et al., 2022). Centrally, there is a

decrease in the muscle voluntary activation, due to a reduced motor cortex output and a reduction in the frequency and synchronization of motoneurons. Consequently, motor units are either not recruited or do not fire often enough, not allowing muscle fibres to produce their maximum force (Boyas & Guével, 2011; Tornero-Aguilera et al., 2022).

Peripheral fatigue in particular, as it occurs within the muscle, origins metabolic changes that cause an increase of the muscle spindle's discharge threshold, disturbing the proprioceptive input from these mechanoreceptors (Balestra et al., 1992; Gribble & Hertel, 2004; Pedersen et al., 1998; Voight et al., 1996). However, a negative impact of muscle fatigue on the information signalled by joint mechanoreceptors cannot be disregarded, since an increase in knee ligament laxity has also been described as a result of fatiguing exercise (Johannsen et al., 1989; Steiner et al., 1986).

Although previous studies have investigated the effects of muscle fatigue on different proprioceptive subcomponents at the knee joint (Bersotti et al., 2022; Da Silva et al., 2021; Paschalis et al., 2010; Torres et al., 2010; Vila-Chã et al., 2011), there is a lack of debate in the existing literature about the effect of different muscle fatigue protocols on the three subcomponents (JPS, kinesthesia, and force sense). This motivated the systematic review of **Chapter 2**, allowing to summarise the effects of muscle fatigue on the knee proprioception of trained and non-trained individuals.

Particularly for JPS, the conducted systematic review (Azevedo et al., 2024) allowed to understand that the included studies applied distinct assessment parameters. This raised the question of whether this observed variability, apart from the influence of muscle fatigue itself, could impact the accuracy of repositioning a previously demonstrated angle. In that sense, before investigating the effects of muscle fatigue on the knee JPS, the influence of different parameters on the accuracy during knee JPS assessments had to be further explored, which led to the study of **Chapter 3**. This study analysed the influence of different JPS protocol-related factors such as: (i) the test position (sitting, prone, or standing), which determines if the test is conducted in weight-bearing

or non-weight-bearing conditions (Lokhande et al., 2013; Olsson et al., 2004); (ii) the motion direction (to flexion and/or to extension), which defines the type of repositioning (concentric or eccentric) (Clark et al., 2016); and (iii) the target angles (intermediate and/or extreme angles of the knee joint ROM) (Gear, 2011). Also, the influence of individual factors such as sex and dominance was investigated to understand whether the inclusion of female participants affects knee JPS assessments due to hormonal influence across the menstrual cycle (Fouladi et al., 2012), and whether there are accuracy differences between limbs justifying the assessment of both limbs or just a single one. Furthermore, this study aimed to establish normative values in the different applied JPS tests for healthy young individuals, allowing the identification of those with reduced proprioception, compromised joint stability, and probable increased risk of knee injuries both during daily activities and sports practice.

The systematic review also led to the observation of conflicting conclusions between the studies investigating the impact of muscle fatigue on the knee JPS, which could be explained by different enlightenments. First, there was a high variability in the applied fatigue protocols, which were either localized and/or general. The localized protocols included a single or several muscle groups, and were performed through concentric, eccentric, or a combination of both contraction-mode exercises. Secondly, the participants of most studies consisted of individuals involved in sports practice, being possible that many of those fatigue protocols were not suitable or intense enough to impact their knee JPS. Another limitation seen in the majority of studies was that muscle fatigue was not confirmed or quantified with objective measures, such as force decrease (Givoni et al., 2007) or surface electromyography (sEMG) (Chang et al., 2012), which might explain the absence of results in some of those studies. Effectively, the sEMG signal has been described to carry information related to muscle fatigue, as myoelectric manifestations can be seen in changes of the signal frequency and amplitude (Al-Mulla et al., 2012; Chang et al., 2012). Finally, the existing studies focused mostly on concentric repositionings to assess JPS. However, eccentric contractions are reported to generate stronger stimuli in the muscle spindles (LaStayo et al., 2003). Therefore, the impact of muscle fatigue was still

unknown on knee JPS assessments whose repositionings were performed eccentrically.

To fill the above-mentioned gaps, the study of **Chapter 4** investigates the effect of different isolated concentric or eccentric fatigue protocols of the quadriceps or hamstrings on the knee JPS of healthy individuals. To confirm the presence of muscle fatigue, during the fatigue protocols, the involved muscles were monitored with sEMG, and the force variation was also quantified. Additionally, knee JPS was assessed in different test positions (sitting and prone), and through concentric and eccentric repositionings, to understand whether a specific muscle fatigue protocol had a greater impact on a particular JPS test. The assessment of JPS was chosen since previous studies have stated that the reproduction of a knee joint angle is more sensitive to fatigue loading than, for example, kinesthesia (Skinner et al., 1986).

Muscle fatigue has similarly been linked with mechanical loss of knee joint stability, for example, causing increased anterior tibial translation (Melnik & Gollhofer, 2007). One of the strategies to maintain joint stability and stiffness during functional activities (Baratta et al., 1988; Smith et al., 2019) is the simultaneous activation of agonist and antagonist muscle groups during voluntary contractions, a mechanism known as muscle coactivation (Psek & Cafarelli, 1993). Particularly in the knee joint, coactivation of the hamstrings during quadriceps contractions enhances joint stability by limiting anterior tibial translation, thereby reducing the tensile load on the anterior cruciate ligament (Yanagawa et al., 2002).

Muscle coactivation of the knee extensors and flexors has formerly been described during isometric (Wu et al., 2017) and concentric/eccentric motions (Alkjær et al., 2012). However, although coactivation of agonists and antagonists has been linked to enhanced movement accuracy (Gribble et al., 2003), the specific contributions of these muscles and their coactivation indices during JPS assessments have not been described yet. Likewise, it remains unknown whether, and how, these contributions and coactivation patterns change following the induction of muscle fatigue, either in the agonist or antagonist muscles.

JPS is usually estimated by calculating different repositioning errors. While absolute angular errors indicate the magnitude of the errors, the relative angular errors reveal directional bias (Vila-Chã et al., 2023). To date, differences in muscle coactivation between individuals with lower and higher errors, and between those who fail the target position in the direction of flexion or extension have not been investigated. However, understanding these differences may help explain the commonly observed variability in the magnitude of errors or directional bias among individuals without a history of knee injuries. This premise motivated the study of **Chapter 5**, in order to understand the muscle coactivation of the knee extensors and flexors during knee JPS assessments, both before and after inducing two different muscle fatigue protocols in healthy individuals. Also, differences in the muscle coactivation were analysed between those with lower and higher magnitudes of repositioning errors, and between those who fail the target positions by describing more flexion or extension.

In summary, the aims of the studies of this thesis are: (i) to systematically review and summarise the evidence about the effect of muscle fatigue on the knee proprioception of trained and non-trained individuals; (ii) to provide normative values in different knee JPS assessments for healthy young individuals, and to investigate which protocol-related factors produce higher accuracy, as well as the influence of individual factors on the knee JPS; (iii) to investigate the effect of different isolated concentric or eccentric fatigue protocols of the quadriceps or hamstrings on the knee JPS; and (iv) to describe muscle coactivation during knee JPS assessments, before and after muscle fatigue, and to analyse the implications for the magnitude of errors and directional bias.

Chapter 2

The effect of muscle fatigue on the knee proprioception: a systematic review

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Abstract

Background: Muscle fatigue has been hypothesized to be a contributing factor for reduced proprioceptive abilities, and to joint injury. This study aimed to systematically review and summarise the evidence about the effect of muscle fatigue on the knee proprioception of trained and non-trained individuals.

Methodology: An electronic search in PubMed, Scopus, Web of Science and EBSCO (Academic Search Complete, CINAHL Plus with Full Text, SPORTDiscus with Full Text and MEDLINE with Full Text) databases and in Google Scholar was conducted from inception to January 2023, using the expression: “fatigue” AND (“proprioception” OR “position sense” OR “repositioning” OR “kinesthesia” OR “detection of passive motion” OR “force sense” OR “sense of resistance”) AND “knee”. Two reviewers screened and extracted data and assessed the risk of bias of the eligible studies according to the Cochrane Collaboration’s risk-of-bias tool.

Results: Forty-two studies fulfilled the eligibility criteria, presenting results for 1060 individuals, and assessed the effect of a localized or general fatigue protocol in one of the subcomponents of proprioception. Regarding joint-position sense, significantly higher repositioning errors were reported after both local and general fatigue protocols. Kinesthesia seems to be more affected when fatigue is induced locally, and force sense is worse when assessed at higher target forces and, specifically, after eccentric protocols.

Conclusions: Muscle fatigue, both induced locally or generally, has a negative impact on the knee proprioception of trained and non-trained individuals. This impact may lead to a defective knee stability, leading to an increased risk of injuries.

Keywords: systematic review; muscle fatigue; proprioception; knee.

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Introduction

Proprioception was first defined by Charles Sherrington in 1906, as the perception of joint and body motion, as well as the body or the body segments' position in space (Sherrington, 1920). In general, three subcomponents of proprioception are distinguished: joint position sense (JPS), which dictates the ability of an individual to understand a particular joint angle, and to reproduce it actively or passively, without the aid of vision (Lephart et al., 1997; Rozzi et al., 2000); kinesthesia, or motion sense, determined as the ability to detect slow passive motion (Lephart et al., 1997; Riemann et al., 2002); and force sense, which refers to a sensation of resistance or weight (Riemann et al., 2002).

Proprioception of the knee is mainly ensured by muscle (Muscle Spindles and Golgi Tendon Organs) (Craig & Rollman, 1999; Gandevia & Burke, 1992; Lephart et al., 1998) and joint mechanoreceptors (Ruffini terminations, Golgi terminations, Paccini terminations, and free terminations), while cutaneous receptors have a minimal contribution (Lephart et al., 1998).

Previous investigations sustain that muscle mechanoreceptors, and particularly the muscle spindles, are the ones providing more proprioceptive input for the Central Nervous System (Craig & Rollman, 1999; Gandevia & Burke, 1992; Lephart et al., 1998), being able to provide afferent information through the entire range of motion of a joint (Proske, 2023), but being specially active in the mid-ranges (Docherty et al., 1998), particularly between 40°-80° of knee flexion (Olsson et al., 2004). On the contrary, joint mechanoreceptors signal information only at the end-ranges of motion (Proske, 2023; Riemann & Lephart, 2002).

Muscle fatigue can be defined as the reduction of a muscle's ability to generate strength and power due to intense physical exercise, resulting in increased discomfort and perceived exertion during exercise, due to peripheral and/or central factors (Gandevia, 2001).

Fatigue has long been hypothesized to be a contributing factor for reduced proprioceptive abilities, and therefore a contributing factor to joint injury and decreased performance (Gear, 2011). Indeed, previous investigations have

suggested that muscle fatigue is related to the high prevalence of injuries, especially in the last 15 minutes of soccer practices or games and even in the last phases of seasons (Ekstrand et al., 2011; Giza et al., 2005; Pedrinelli et al., 2013).

Effectively, it has been previously described that peripheral fatigue, as it occurs within the muscle, leads to metabolic changes that cause an increase of the muscle spindle's discharge threshold, disturbing the proprioceptive input coming from these mechanoreceptors, with negative implications on proprioceptive acuity (Balestra et al., 1992; Gribble & Hertel, 2004; Pedersen et al., 1998; Voight et al., 1996). Furthermore, other investigations also show increased knee ligament laxity due to fatiguing exercise (Johannsen et al., 1989; Steiner et al., 1986), which may also disturb the information signalled by joint mechanoreceptors.

A recent systematic review regarding the effect of fatigue on the hip, knee, and ankle joints has been published, suggesting that fatigue has a negative effect on JPS specifically at the knee (Sayyadi et al., 2024). However, although the authors have addressed the effect of fatigue on the JPS in the joints of the lower limb, they have not analysed the effect of fatigue on the other proprioceptive sub-components. It is also important to note that the effects of specific fatigue protocols were not discussed to understand which protocols may have a greater impact on JPS. The study also presented a meta-analysis of the results, although the authors themselves admitted a high heterogeneity in the protocols and ways of assessment of JPS, which may question the conduct of a meta-analysis. In that sense, there is still a lack of a systematic review of the existing literature discussing the effect of different muscle fatigue protocols on all proprioceptive sub-components of the knee joint. Therefore, this study aimed to systematically review and summarise the evidence regarding the effect of muscle fatigue on the knee proprioception of trained and non-trained individuals.

Methods

This review was reported based on the updated guidelines for the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) (Page et al., 2021). Registration in the International Prospective Register of Systematic Reviews (PROSPERO) was also conducted (Registration Number: CRD42023392610).

Search Strategy

The PICO strategy was used to define the components of the research: Participants (P) = trained and non-trained individuals; Interventions (I) = muscle fatigue protocols; Comparators (C) = without restrictions; Outcome (O) = knee joint-position sense, kinesthesia, and/or force sense.

An electronic search was conducted in PubMed, Scopus, Web of Science and EBSCO (Academic Search Complete, CINAHL Plus with Full Text, SPORTDiscus with Full Text and MEDLINE with Full Text) databases from inception to January 20, 2023, using the expression: “fatigue” AND (“proprioception” OR “position sense” OR “repositioning” OR “kinesthesia” OR “detection of passive motion” OR “force sense” OR “sense of resistance”) AND “knee”. In addition, the first 300 results on the Google Scholar search engine were analysed to find relevant, grey, and published literature that did not appear in the database search (Haddaway et al., 2015).

Eligibility Criteria

The structure of PICOS was used to define the following criteria:

1. Participants: trained and non-trained individuals of any age and both sexes;
2. Intervention: muscle fatigue protocols, with sufficiently detailed information;

3. Comparator: without restrictions;
4. Outcomes: assessment of at least one knee proprioceptive subcomponent (joint-position sense, kinesthesia, or force sense);
5. Study design: randomized controlled or non-randomized trials, case-control, cohort, or cross-sectional studies (published in English, Portuguese, Spanish, Italian, or French).

Books, case reports, case series, review articles, conference, abstracts, study protocols, studies where participants were assessed with knee braces, conducted in patients with neurological diseases, or studies that did not have sufficiently detailed information regarding the muscle fatigue protocol were excluded. No publication date restrictions were defined.

Study Selection and Data Extraction

All references were exported to a data management software (EndNote X9), and duplicates were removed. The review was conducted following three steps. Records were identified through database search and reference screening (Identification), and two reviewers (JA; IMS) independently examined titles and abstracts. In case of ambiguous eligibility, the study's full text was obtained. Based on eligibility criteria, irrelevant studies were excluded (Screening). Relevant full texts were analysed for eligibility, and all relevant studies were included in the systematic review (Inclusion). The same reviewers extracted the data from the included studies. Data regarding study information (author and year), sample (size, age, sex), muscle fatigue protocols, instruments/outcomes, and results were collected. In case of disagreement over the eligibility of specific studies or data extraction, a discussion was carried out between the reviewers until a consensus was reached.

Quality analysis and risk of bias assessment

A quality analysis of the non-randomized studies was conducted using the Methodological Index for Non-Randomized Studies (MINORS) (Slim et al., 2003). Eight items of MINORS are related to non-comparative studies, and 4 additional items are related to comparative studies. The items can be graded with a score of 0 (not reported), 1 (reported, but inadequate), and 2 (reported and adequate), which gives a possible total of 16 for non-comparative studies, and 24 for comparative studies. In the non-comparative studies, the scores can be interpreted as: 0 - 4, very low quality; 5 - 8, low quality; 9 - 12, fair quality; and 13 - 16, high quality (Khan et al., 2015). In the comparative studies, the scores can be interpreted as 0 - 6, very low quality; 7 - 12, low quality; 13 - 18, fair quality, and 19 - 24, high quality (Khan et al., 2015).

For the randomized studies, the risk of bias was assessed with the revised Cochrane risk-of-bias tool version 2 (RoB2) (Sterne et al., 2019). RoB2 provides a bias risk assessment within 5 domains (domain 1: randomisation process; domain 2: deviations from the intended interventions; domain 3: missing outcome data; domain 4: outcome measurement; domain 5: selection of the reported results). The algorithm of the provided software categorizes the studies with a “low risk”, “some concerns”, or a “high risk” of bias (Sterne et al., 2019).

Two independent authors (JA and IMS) performed the quality assessment of the non-randomized studies according to MINORS (Slim et al., 2003) and the risk of bias assessment of the randomized studies with the RoB2 tool (Sterne et al., 2019). Consensus discussions were held in case of disagreement.

Data synthesis

Data synthesis was performed by presenting tables and summarising the studies' results using a qualitative approach.

The heterogeneity in the muscle fatigue protocols, the assessment of the considered outcome measures (JPS, kinesthesia, and force sense), and the analysed samples excluded a meta-analysis. For instance, for the knee JPS

assessments, studies used active or passive repositioning methods, with ipsilateral or contralateral repositionings, tests in weight-bearing and non-weight-bearing conditions, and target angles ranged from 10° to 80° of knee flexion. Regarding kinesthesia, the starting test positions also ranged from 20° to 70° of knee flexion, and were assessed either to flexion or extension. Finally, in the knee force sense assessments, different target forces were used (between 10% and 30% of the maximum voluntary isometric contraction – MVIC), as well as tests were conducted for flexion and extension.

A qualitative synthesis of the available evidence was implemented, considering participants' characteristics, outcome measures, assessment instruments, muscle fatigue protocols, and main study results, and presented in the text and summary table.

Results

Studies' Selection

A total of 943 studies were identified and, after the removal of duplicates, 455 studies were retained. During the screening process, 401 publications were excluded for not being related to the research question, and the full texts of 54 studies were reviewed in detail. After careful analysis, 12 studies were excluded (5 because they were in the Korean language, 2 in Persian, 1 in Chinese, 2 studies used knee braces, 1 study was an extended abstract, and, finally, 1 study did not describe the protocol used to induce muscle fatigue). Finally, 42 studies were included in the systematic review. The selection process is summarized in Figure 1.

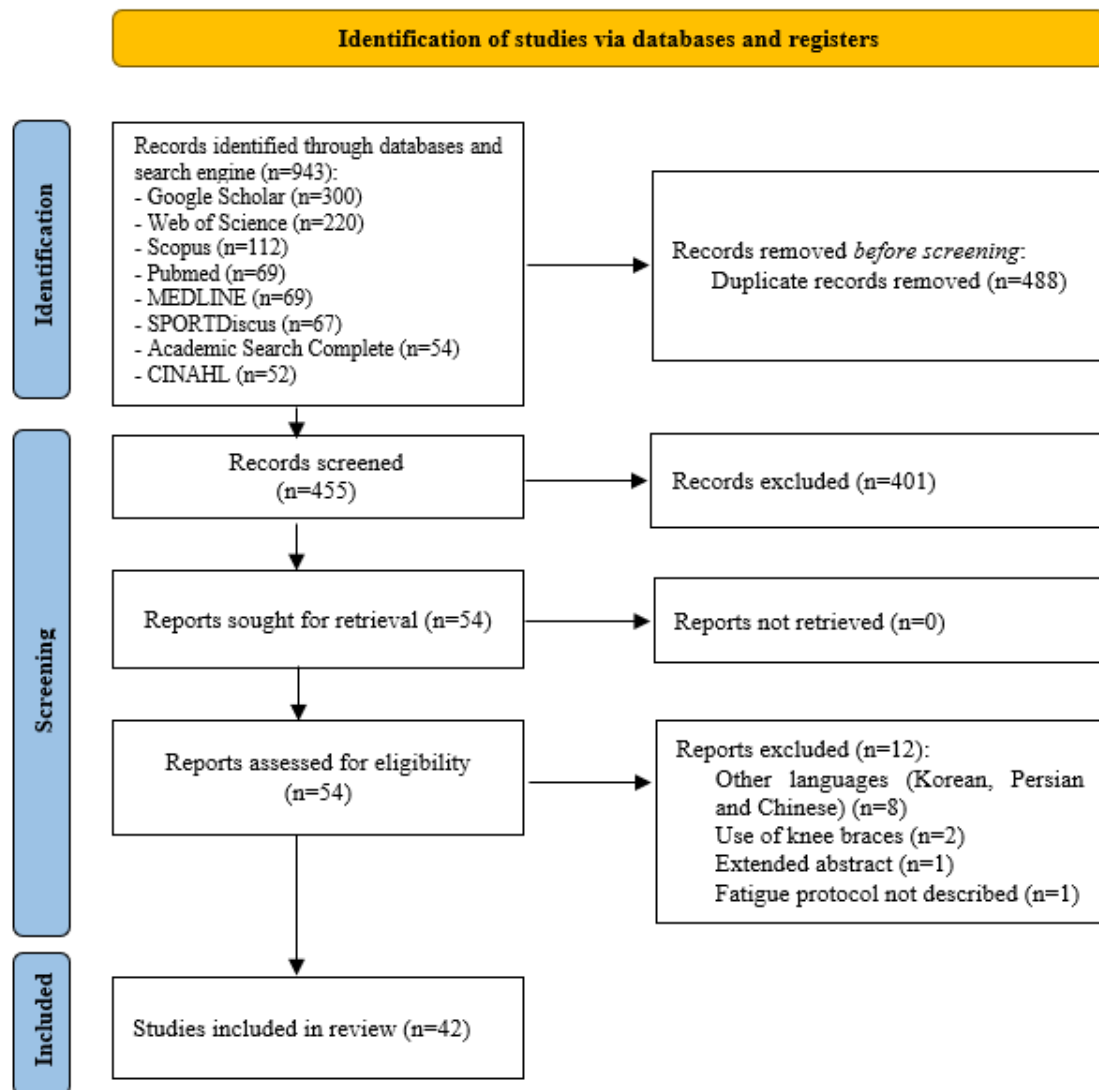


Figure 1. PRISMA flow diagram of the literature selection process.

Quality analysis and risk of bias assessment results

Quality assessment of the 36 non-randomized included studies according to MINORS (Slim et al., 2003) is presented in Table 1. Five studies were considered comparative (Bayramoglu et al., 2007; Bozkurt et al., 2020; Dieling et al., 2014; Mohammadi et al., 2013; Paschalis et al., 2013), while the rest were non-comparative studies. The mean [range] MINORS score was 10.5 [10–12] for non-comparative studies and 16.8 [16–18] for comparative studies. For both comparative and non-comparative studies, the quality was considered fair.

Overall, the methodological strengths related to the items 1 to 7 included: the reporting of a precise aim (item 1), the inclusion of consecutive patients (item 2), the prospective collection of data (item 3), the use of appropriate endpoints (item 4), and the adequate follow-ups (item 6). Regarding the five comparative studies, all of them had the highest score in item 10 since the groups were contemporary.

Regarding the methodological weaknesses, all studies did not assure an unbiased assessment of the study endpoints (item 5), and in 27 studies, the loss of follow-up was not reported (item 7). Regarding the items related to the five comparative studies, in all studies the sample size was not calculated or not reported (item 8), one study was assessed with an inadequate control group (item 9), one study did not report baseline equivalence between groups and two studies reported demographic variables but baseline equivalence was not met (item 11), with one of these studies not adjusting the statistical analyses accordingly (item 12).

Risk of bias assessment of the six randomized included studies according to RoB2 (Sterne et al., 2019) is presented in the traffic-light and summary plots of Figures 2 and 3, respectively.

Author (Year)	D1	D2	D3	D4	D5	Overall	
Ali et al. (2013)							 Low risk
Marks (1994)							 Some concern
Marks and Quinney (1993)							 High risk
Paschalis et al. (2010)							
Romero-Franco and Jiménez-Reyes (2017)							
Shokri et al. (2018)							

Figure 2. Traffic-light plot according to the Cochrane risk-of-bias (RoB2) tool version 2 (Sterne et al., 2019) D1: (D1: Randomisation process; D2: Deviations from the intended interventions; D3: Missing outcome data; D4: Measurement of the outcome; D5: Selection of the reported results).

Four of the six randomized studies were judged as high risk of bias, and two had a low risk of bias (Figure 2). All studies were considered low risk regarding domains 2, 3, and 4. Four studies were judged as high risk regarding domain 1 since the randomization process was not sufficiently detailed, and domain 5, as some inconsistencies were found regarding the selection of the reporting results.



Figure 3. Summary plot according to the Cochrane risk-of-bias (RoB2) tool version 2 (Sterne et al., 2019).

Studies' description

Participants' characteristics

The 42 included studies have a total of 1060 participants, with the sample size ranging from 11 (Skinner et al., 1986) to 100 participants (Draz et al., 2014). Of these, 506 were male participants and 412 were female. Three studies did not report the sex of participants (Draz et al., 2014; Kiyama et al., 2014; Roberts et al., 2003).

The age of participants ranged from 16 to 74 years. Thirty-nine studies included only young participants without any knee injury/pathology; and three studies included older individuals, in which two involved subjects with knee osteoarthritis (Bayramoglu et al., 2007; Bozkurt et al., 2020), and one study healthy older

individuals (Ribeiro et al., 2007). Paschalis et al. (2013) also included subjects with different body mass indices (BMI), from underweight to overweight.

Regarding sports practice, five studies investigated the effects of muscle fatigue in soccer players (Azevedo et al., 2018; Carrasco et al., 2021; Gear, 2004, 2011; Salgado et al., 2015); two studies in basketball players (Gear, 2004, 2011); one study in volleyball players (Ribeiro et al., 2008); one study in handball players (Niederseer et al., 2014); and one study in sprinters (Romero-Franco & Jiménez-Reyes, 2017). Also, two studies were conducted in male conscripts (Mohammadi et al., 2013) or Navy Seals (Skinner et al., 1986). The study of Bottoni et al. (2015) was conducted on sports students, and the study of Dieling et al. (2014) on ballet dancers.

Outcome measures

The majority of the studies (36 out of 42 studies) investigated the effect of muscle fatigue on the knee JPS, while kinesthesia was assessed in six studies (Allison, Abt, et al., 2016; Da Silva, Colson, et al., 2022; Dieling et al., 2014; Roberts et al., 2003; Skinner et al., 1986; Torres et al., 2010), and force sense in four studies (Allison, Sell, et al., 2016; Kiyama et al., 2014; Shokri et al., 2018; Torres et al., 2010).

Regarding JPS, authors considered as outcomes the absolute angular errors (AAE), calculated as the absolute value of the difference between the value of the target angle and the angle reproduced by the participant (Bennell et al., 2005); the relative angular errors (RAE), meaning the arithmetic difference between the value of the target angle and the angle reached by the participant (Bennell et al., 2005), evidencing if participants underestimated or overestimated the target angle; and variable angular errors (VAE), the standard deviation of the different repositionings (Olsson et al., 2004).

For kinesthesia, authors reported as outcome the threshold to detect passive motion (TTDPM), described as the time or angle between the beginning of the

joint movement and its detection (Da Silva, Colson, et al., 2022; Dieling et al., 2014).

Regarding force sense, authors considered the force sense error, defined as the difference between the target and output force (Kiyama et al., 2014).

Instruments

The isokinetic dynamometer was the most used instrument, with 17 studies using it to assess JPS, four studies to assess kinesthesia, and three studies for force sense. Indeed, this instrument has been described to present excellent trial reliability and day-to-day reliability (ICC = 0.99) (Drouin et al., 2004), and its accuracy in determining joint position was determined to be $\pm 1^\circ$ (Gear, 2011).

Self-designed devices by the authors were used in one study to assess JPS (Skinner et al., 1986), in two studies to assess kinesthesia (Roberts et al., 2003; Vila-Chã et al., 2011), and in one study to assess force sense (Kiyama et al., 2014).

Video cameras were used in eight studies only to assess JPS (Bottoni et al., 2015; Changela et al., 2013; Da Silva, Monjo, et al., 2022; Miura et al., 2004; Ribeiro et al., 2007; Ribeiro et al., 2008; Romero-Franco & Jiménez-Reyes, 2017; Salgado et al., 2015).

Potentiometers were also used in four studies to assess JPS (Allen et al., 2010; Givoni et al., 2007; Marks, 1994; Marks & Quinney, 1993); while inclinometers (Bazneshin et al., 2015; Da Silva et al., 2021; Niederseer et al., 2014) and electrogoniometers (Ju et al., 2010; Lattanzio et al., 1997; Vila-Chã et al., 2011) were both used in three studies to assess JPS.

Finally, JPS was assessed using a goniometer in two studies (Ali et al., 2013; Changela et al., 2013) and inertial sensors in one study (Azevedo et al., 2018).

Knee JPS assessment

Knee JPS assessments were conducted through active or passive repositioning of one or more memorized angles. The majority of the included studies adopted an active repositioning, while five studies considered a passive repositioning (Bayramoglu et al., 2007; Dieling et al., 2014; Gear, 2004; Ju et al., 2010; Mohammadi et al., 2013). Four studies adopted a contralateral limb repositioning (Allen et al., 2010; Da Silva, Monjo, et al., 2022; Da Silva et al., 2021; Givoni et al., 2007), while most studies adopted an ipsilateral repositioning.

Additionally, knee JPS was evaluated through open kinetic chain techniques (non-weight bearing tests), in the seated (Salgado et al., 2015), in prone (Da Silva, Monjo, et al., 2022) or in supine (Ali et al., 2013) positions, which was considered in 34 studies; or in closed kinetic chain (weight-bearing tests), in the standing position, which was assessed in four studies (Changela et al., 2013; Lattanzio et al., 1997; Romero-Franco & Jiménez-Reyes, 2017; Vila-Chã et al., 2011).

Regarding test positions, extreme angles ranged from 15° to 30° of knee flexion. Regarding intermediate angles, the studies ranged from 38° to 79° of knee flexion. Other authors used random angles within the knee ROM (Niederseer et al., 2014) or in specific intervals of knee flexion, like 10°-60° (Lattanzio et al., 1997), 10°-80° (Ju et al., 2010; Miura et al., 2004), 40° and 60° (Ribeiro et al., 2007; Ribeiro et al., 2008; Salgado et al., 2015), 45° to 75° (Marks, 1994; Marks & Quinney, 1993), and finally, 30° and 70° (Bottoni et al., 2015).

Knee Kinesthesia Assessment

Regarding kinesthesia assessment, two starting positions were considered extreme: 20° (Allison, Abt, et al., 2016; Roberts et al., 2003) and 30° of knee flexion (Da Silva, Colson, et al., 2022; Dieling et al., 2014; Torres et al., 2010). The other angles were considered as being intermediate in the knee ROM: 40° (Roberts et al., 2003); 45° (Dieling et al., 2014), 60° (Skinner et al., 1986), and 70° of knee flexion (Torres et al., 2010).

TTDPM was assessed for flexion in three studies (Allison, Abt, et al., 2016; Da Silva, Colson, et al., 2022; Roberts et al., 2003) and for extension in six studies (Allison, Abt, et al., 2016; Da Silva, Colson, et al., 2022; Dieling et al., 2014; Roberts et al., 2003; Skinner et al., 1986; Torres et al., 2010).

Knee Force Sense Assessment

Force sense was measured at different target forces, such as 10% (Kiyama et al., 2014), 15% (Allison, Sell, et al., 2016), 20% (Torres et al., 2010), and 30% of the MVIC (Kiyama et al., 2014). The study of Shokri et al. (2018) did not describe the assessed target force.

Kiyama et al. (2014) and Torres et al. (2010) assessed force sense to knee extension, while Allison, Sell, et al. (2016) assessed both to knee flexion and extension.

Muscle Fatigue Protocols

Most studies applied a localized muscle fatigue protocol using the isokinetic dynamometer, targeting the knee flexors (Allen et al., 2010; Paschalis et al., 2010; Ribeiro et al., 2011), the knee extensors (Bersotti et al., 2022; Kiyama et al., 2014; Paschalis et al., 2007; Paschalis et al., 2013; Paschalis et al., 2010; Ribeiro et al., 2011; Torres et al., 2010; Vila-Chã et al., 2011), or both muscle groups (Bozkurt et al., 2020; Cowan, 2009; Da Silva, Colson, et al., 2022; Da Silva, Monjo, et al., 2022; Da Silva et al., 2021; Dieling et al., 2014; Gear, 2004, 2011; Ju et al., 2010; Ribeiro et al., 2007; Shokri et al., 2018). Azevedo et al. (2018) induced local muscle fatigue by repeated squats while sitting and standing. Givoni et al. (2007) investigated the influence of two protocols, one concentric and one eccentric, where subjects had to step up or step down 792 steps, respectively, two steps at a time.

Some studies also investigated the effect of general fatigue protocols. In the case of Miura et al. (2004), both local and general protocols were performed, with the

last one consisting of running uphill on a treadmill. Similarly, Carrasco et al. (2021) submitted their participants to a continuous run on a treadmill. Related to these previous studies, Bottoni et al. (2015) explored the effect of two general fatigue protocols where participants had to walk uphill or downhill on a treadmill. Other four studies submitted their participants to cycling protocols (Bayramoglu et al., 2007; Changela et al., 2013; Lattanzio et al., 1997; Roberts et al., 2003)

Regarding the other general fatigue protocols, Salgado et al. (2015), Niederseer et al. (2014), and Ribeiro et al. (2008) opted for a simulated soccer, handball, and volleyball match, respectively. Ali et al. (2013) applied the Functional Fatigue Protocol. Also, the Navy SEALs of the study of Skinner et al. (1986) performed a fatiguing protocol consisting of sprinting, and the study of Mohammadi et al. (2013) in male conscripts consisted of military physical activities. Allison, Abt, et al. (2016) applied general exercises to induce muscle fatigue involving running, push-ups, sit-ups, and step-ups, while Romero-Franco and Jiménez-Reyes (2017) performed a plyometric exercise protocol.

Unlike the other studies, Draz et al. (2014) investigated the influence of acute back muscle fatigue on the knee proprioception.

Table 2 summarizes the included studies in this systematic review, presenting details about the characteristics of the sample, the performed fatigue protocols, the considered outcomes, the used instruments, and the reported results.

Table 1. Quality assessment of the included studies according to the Methodological Index for Non-Randomized Studies (MINORS) (Slim et al., 2003).

Autor (year)	Study Design	Item 1	Item 2	Item 3	Item 4	Item 5	Item 6	Item 7	Item 8	Item 9	Item 10	Item 11	Item 12	Score	Quality
Allen et al. (2010)	Quasi-experimental	2	2	2	2	0	2	0	NA	NA	NA	NA	NA	10	Fair
Allison, Abt, et al. (2016)	Quasi-experimental	2	2	2	2	0	2	0	NA	NA	NA	NA	NA	10	Fair
Allison, Sell, et al. (2016)	Quasi-experimental	2	2	2	2	0	2	0	NA	NA	NA	NA	NA	10	Fair
Azevedo et al. (2018)	Quasi-experimental	2	2	2	2	0	2	0	NA	NA	NA	NA	NA	10	Fair
Bayramoglu et al. (2007) *	Quasi-experimental	2	2	2	0	0	2	0	0	2	2	2	2	16	Fair
Bazneshin et al. (2015)	Quasi-experimental	2	2	2	2	0	2	0	NA	NA	NA	NA	NA	10	Fair
Bersotti et al. (2022)	Quasi-experimental	2	2	2	2	0	2	0	NA	NA	NA	NA	NA	10	Fair
Bottoni et al. (2015)	Quasi-experimental	2	2	2	2	0	2	0	NA	NA	NA	NA	NA	10	Fair
Bozkurt et al. (2020) *	Quasi-experimental	2	2	2	2	0	2	0	0	2	2	1	1	16	Fair
Carrasco et al. (2021)	Quasi-experimental	2	2	2	2	0	2	0	NA	NA	NA	NA	NA	10	Fair
Changela et al. (2013)	Quasi-experimental	2	2	2	2	0	2	0	NA	NA	NA	NA	NA	10	Fair
Cowan (2009)	Quasi-experimental	2	2	2	2	0	2	0	NA	NA	NA	NA	NA	10	Fair
Da Silva, Colson, et al. (2022)	Quasi-experimental	2	2	2	2	0	2	0	NA	NA	NA	NA	NA	10	Fair
Da Silva, Monjo, et al. (2022)	Quasi-experimental	2	2	2	2	0	2	0	NA	NA	NA	NA	NA	10	Fair

Table 1 (Cont.). Quality assessment of the included studies according to the Methodological Index for Non-Randomized Studies (MINORS) (Slim et al., 2003).

Autor (year)	Study Design	Item 1	Item 2	Item 3	Item 4	Item 5	Item 6	Item 7	Item 8	Item 9	Item 10	Item 11	Item 12	Score	Quality
Da Silva et al. (2021)	Quasi-experimental	2	2	2	2	0	2	0	NA	NA	NA	NA	NA	10	Fair
Dieling et al. (2014) *	Quasi-experimental	2	2	2	2	0	2	2	0	2	2	0	2	18	Fair
Draz et al. (2014)	Quasi-experimental	2	2	2	2	0	2	0	NA	NA	NA	NA	NA	10	Fair
Gear (2004)	Quasi-experimental	2	2	2	2	0	2	0	NA	NA	NA	NA	NA	10	Fair
Gear (2011)	Quasi-experimental	2	2	2	2	0	2	0	NA	NA	NA	NA	NA	10	Fair
Givoni et al. (2007)	Quasi-experimental	2	2	2	2	0	2	2	NA	NA	NA	NA	NA	12	Fair
Ju et al. (2010)	Quasi-experimental	2	2	2	2	0	2	0	NA	NA	NA	NA	NA	10	Fair
Kiyama et al. (2014)	Quasi-experimental	2	2	2	2	0	2	0	NA	NA	NA	NA	NA	10	Fair
Lattanzio et al. (1997)	Quasi-experimental	2	2	2	2	0	2	2	NA	NA	NA	NA	NA	12	Fair
Miura et al. (2004)	Quasi-experimental	2	2	2	2	0	2	2	NA	NA	NA	NA	NA	12	Fair
Mohammadi et al. (2013) *	Cohort	2	2	2	2	0	2	0	0	2	2	2	2	18	Fair
Niederseer et al. (2014)	Quasi-experimental	2	2	2	2	0	2	2	NA	NA	NA	NA	NA	12	Fair
Paschalis et al. (2007)	Quasi-experimental	2	2	2	2	0	2	0	NA	NA	NA	NA	NA	10	Fair
Paschalis et al. (2013) *	Quasi-experimental	2	2	2	2	0	2	0	0	1	2	1	2	16	Fair
Ribeiro et al. (2007)	Quasi-experimental	2	2	2	2	0	2	2	NA	NA	NA	NA	NA	12	Fair

Table 1 (Cont.). Quality assessment of the included studies according to the Methodological Index for Non-Randomized Studies (MINORS) (Slim et al., 2003).

Autor (year)	Study Design	Item 1	Item 2	Item 3	Item 4	Item 5	Item 6	Item 7	Item 8	Item 9	Item 10	Item 11	Item 12	Score	Quality
Ribeiro et al. (2008)	Quasi-experimental	2	2	2	2	0	2	2	NA	NA	NA	NA	NA	12	Fair
Ribeiro et al. (2011)	Quasi-experimental	2	2	2	2	0	2	0	NA	NA	NA	NA	NA	10	Fair
Roberts et al. (2003)	Quasi-experimental	2	2	2	2	0	2	0	NA	NA	NA	NA	NA	10	Fair
Salgado et al. (2015)	Quasi-experimental	2	2	2	2	0	2	2	NA	NA	NA	NA	NA	12	Fair
Skinner et al. (1986)	Quasi-experimental	2	2	2	2	0	2	0	NA	NA	NA	NA	NA	10	Fair
Torres et al. (2010)	Quasi-experimental	2	2	2	2	0	2	2	NA	NA	NA	NA	NA	12	Fair
Vila-Chã et al. (2011)	Quasi-experimental	2	2	2	2	0	2	0	NA	NA	NA	NA	NA	10	Fair

The items were scored 0 (not reported), 1 (reported but inadequate), or 2 (reported and adequate). NA - Not applicable; Comparative studies were marked with an asterisk (*).

Table 2. Summary table of the included studies in the systematic review with main findings.

Autor (year)	Sample	Muscle Fatigue Protocol	Instruments/Outcomes	Results
Ali et al. (2013)	28 healthy university students (F) (21.08 ± 2.2 years) n = 14 (CG: rest) n = 14 (EG: fatigue protocol)	Functional Fatigue Protocol.	<u>Joint-Position Sense:</u> - active repositioning; OKC - initial position: supine - target position: 20°/ 45° of KF - instrument: goniometer - outcomes: AAE of the DL	AAE significantly increased post-fatigue only for the 45° angle ($p=0.01$).
Allen et al. (2010)	34 healthy individuals (20M; 14F) (age not reported)	Concentric contractions of the knee flexors at 60°/s and knee joint range between 10° to 90° of flexion, until a 30% fall in MVIC torque.	<u>Joint-Position Sense:</u> - active/contralateral repositioning; OKC - initial position: 100° of KF - target position: 45° of KF - instrument: potentiometers - outcomes: RAE (reference limb angle minus the indicator limb angle)	RAE post-fatigue were significantly different from RAE pre-fatigue ($p\leq 0.05$). Exercise of knee muscles made the subjects perceive their knees more flexed.
Allison, Abt, et al. (2016)	20 healthy physically active athletes (F) (28.7 ± 5.6 years)	7 stations: 1) 5min run at 95% VO ₂ pace; 2) 3min run at 110% VO ₂ pace; 3) 2min of push-ups; 4) 2min of sit-ups; 5) 3min of 12-in step-ups; 6) 3min run at 110% VO ₂ pace; 7) 2min run at 115% VO ₂ pace.	<u>Kinesthesia:</u> - initial position: 20° of KF - random direction of passive motion (either to knee flexion or extension, 0.25°/s) - instrument: isokinetic dynamometer - outcomes: TTDPM of the DL	TTDPM did not significantly change post-fatigue, neither to extension ($p=0.601$) nor flexion ($p=0.469$).
Allison, Sell, et al. (2016)	20 healthy and physically active individuals (10M; 10F) (23.35 ± 2.70 years)	3 bouts of isokinetic knee flexion/extension with 40s-rest between bouts: -1 st and 2 nd bouts - 40 maximal-effort reps; -3 rd bout, reps until the PT value of 3 consecutive reps fell below 25% of the baseline PT.	<u>Force Sense:</u> - target torque: 15% of MVIC for quadriceps (to extension) and for hamstrings (to flexion) - testing position: 45° of KF - instrument: isokinetic dynamometer - outcomes: force-sense error of the DL	Force sense error did not significantly change post-fatigue, neither to knee flexion ($p=0.907$) nor extension ($p=0.940$).

Table 2 (Cont.). Summary table of the included studies in the systematic review with main findings.

Autor (year)	Sample	Muscle Fatigue Protocol	Instruments/Outcomes	Results
Azevedo et al. (2018)	60 healthy individuals (31M; 29F): n = 29 semi-professional soccer players (21.0; 8.0 years) n = 31 healthy non-trained individuals (22.0; 3.0 years)	Repetitive sit-to-stand fatigue task, with a rhythm controlled by a 30-bpm metronome until exhaustion or after 30 min.	<u>Joint-Position Sense:</u> - active repositioning; OKC - initial position: 90° of knee flexion - target position: 20°/ 45° of knee flexion - instrument: inertial sensors - outcomes: AAE/RAE/VAE of the DL and NDL	AAE ($p=0.034$) and RAE ($p=0.017$) significantly increased post-fatigue only in the non-trained at 45° angle of the DL. Soccer players underestimated the target position, and the non-trained overestimated. In the soccer players, a significant increase of VAE post-fatigue at 45° angle in the DL ($p=0.002$) and at 20° of the NDL ($p=0.001$). Significantly worse AAE, RAE, and VAE at the 45° angle than at 20° ($p<0.05$). No differences in the accuracy between limbs in the soccer players, but significantly worse acuity in DL than the NDL at 45° in the non-trained ($p=0.050$). No sex effect was found.
Bayramoglu et al. (2007)	80 healthy individuals (16M; 64F): n = 50 patients with bilateral knee OA (60.22 ± 8.43 years) n = 30 (CG) healthy age-matched volunteers (57.86 ± 9.22 years)	Moderate intensity exercise protocol: 5 min on the cycle ergometer, pedalling between 35-45 rpm, and not exceeding a HR of 100 bpm.	<u>Joint-Position Sense/Kinesthesia:</u> - passive repositioning; OKC - the dynamometer moved the leg 2 ways: extension-to-flexion and flexion-to-extension along the 0-90° ROM at 5°/s - target position: 45° of KF - instrument: isokinetic dynamometer - outcomes: AAE of the DL and NDL	AAE did not differ neither between the OA participants and the CG, nor between pre- and post-fatigue ($p>0.05$).
Bazneshin et al. (2015)	34 healthy individuals (M) (22.15 ± 1.97 years)	Repeated knee extensions with a weight of 70% of the quadriceps MVIC until exhaustion. Then, repeated knee extensions with a weight of 50% of quadriceps MVIC, until MVIC reached 50% or less of the baseline value.	<u>Joint-Position Sense:</u> - active repositioning; OKC - initial position: 90° of KF - target position: 45° of KF - instrument: digital inclinometer - outcomes: AAE/RAE of the DL	AAE ($p<0.001$) and RAE ($p=0.006$) significantly increased post-fatigue.

Table 2 (Cont.). Summary table of the included studies in the systematic review with main findings.

Autor (year)	Sample	Muscle Fatigue Protocol	Instruments/Outcomes	Results
Bersotti et al. (2022)	15 healthy individuals (M) (23.4 ± 3.8 years)	Concentric maximum contractions performed at 60°/s of knee extension until equal to or less than 50% of the baseline PT for 5 consecutive reps.	<u>Joint-Position Sense:</u> - active repositioning; OKC - initial position: 90° of KF - target position: 60° of KF - instrument: isokinetic dynamometer - outcomes: AAE/VAE of the DL	AAE ($p=0.20$) and VAE ($p=0.50$) did not significantly change post-fatigue.
Bottoni et al. (2015)	24 healthy sport students (F) (23 ± 2.5 years)	Protocols were performed on a treadmill in a controlled temperature (25°C) and humidity (50%) environment: - <u>uphill walking</u> for 30min at 20% inclination, 3 km/h; - <u>downhill walking</u> for 30min at 20% inclination, 3 km/h.	<u>Joint-Position Sense:</u> - active repositioning; OKC - initial position: 90° of KF - target position: angle between 30° and 70° of KF - instrument: camera - outcomes: AAE/RAE/VAE of the DL	AAE significantly increased after downhill walking, in comparison with the beginning ($p=0.035$). After uphill walking no differences were observed in comparison with the beginning ($p=0.172$) or the downhill walking ($p=0.165$). RAE showed that subjects tended to overestimate their joint position, and that this overestimation was significantly higher after downhill walking than at the beginning ($p=0.002$) or after uphill walking ($p=0.007$). No differences in the RAE were seen from the beginning to the uphill walking ($p=0.785$). VAE did not change during the test ($p=0.674$).
Bozkurt et al. (2020)	23 individuals (F): n = 12 patients with knee OA (54.0 (49.0; 62.0) years) n = 11 healthy post-menopausal women (53.0 (49.0; 66.0) years)	6 sets of 10 eccentric maximal voluntary contractions of knee extensors, flexors at 60°/s with 1 min rest between sets.	<u>Joint-Position Sense:</u> - active repositioning; OKC - initial position: 90° of KF - target position: 45° of KF - instrument: isokinetic dynamometer - outcomes: AAE of the DL	AAE significantly increased post-fatigue in both groups ($p<0.05$).

Table 2 (Cont.). Summary table of the included studies in the systematic review with main findings.

Autor (year)	Sample	Muscle Fatigue Protocol	Instruments/Outcomes	Results
Carrasco et al. (2021)	22 healthy semi-professional soccer players (M) (24 ± 2.7 years)	- <u>local fatigue protocol</u> (3 phases): - 1st phase - pedalling for 5 min on a cycle ergometer (resistance of 70 W); - 2nd phase - in the isokinetic dynamometer, the PT of the quadriceps under concentric activation at 240°/s, subjects had to perform 5 maximum reps, being the PT, the maximum value reached in all of them; - 3rd phase - successive flexion/extension movements (240°/s) until quadriceps torque was less than 50% PT value. - <u>general fatigue protocol</u>: continuous running on a treadmill (10min at 10km/h, 5min at 15km/h, 5min at 12km/h, 5min at 15 km/h, 5min at 12km/h, and so on until exhaustion)	<u>Joint-Position Sense:</u> - active repositioning; OKC - initial position: 90° of knee flexion - target position: 30° of KF - instrument: isokinetic dynamometer - outcomes: AAE/RAE/VAE of the DL	Significant differences were found after both types of fatigue in AAE ($p=0.001$ for local fatigue; $p\leq 0.001$ for general fatigue). Regardless of the type of fatigue, RAE did not significantly change ($p=0.155$ for local fatigue; $p=0.271$ for general fatigue). Both types of fatigue caused similar RAE and in the same direction, with subjects tending to overestimate the target position. No significant differences were seen in the AAE ($p=0.194$), RAE ($p=0.989$), or VAE ($p=0.90$) between the local and general fatigue protocols.

Table 2 (Cont.). Summary table of the included studies in the systematic review with main findings.

Autor (year)	Sample	Muscle Fatigue Protocol	Instruments/Outcomes	Results
Changela et al. (2013)	30 healthy physiotherapy students (21M; 9F) (19-23 years)	Cycling on a static cycle as fast as possible, until subjects reached up to a level of exceeding 60% of HRmax and a level of exertion of 14-17 on the Borg scale.	<u>Joint-Position Sense:</u> - active repositioning; CKC - initial position: standing (weight-bearing test) - target position: 30° of KF - instrument: goniometer and video camera - outcomes: AAE of the right knee	AAE significantly increased post-fatigue ($p<0.001$).
Cowan (2009)	16 healthy individuals (M) (25.8 years $\pm$ 4.5 years)	Repeated maximal contractions to knee extension/flexion at 60°/s, until the knee flexion and extension force fell below 50% of the previously maximal force output.	<u>Joint-Position Sense:</u> - active repositioning; OKC - initial position: 90° of KF - target position: 3 angles in the intervals between 0°-30° (20°); 31°-60° (38°); 61°-90° (79°) of KF - instrument: isokinetic dynamometer - outcomes: AAE/RAE of the DL	The 38° angle was the least accurately reproduced of the 3 angles. AAE did not significantly change post-fatigue in any of the 3 angles. At 20° and 38° angles, acuity improved $0.42^\circ \pm 1.37$ and $0.41^\circ \pm 1.42$, respectively, while an overall reduction in accuracy of $0.24^\circ \pm 1.31$ was reported at the 79° angle. 40% of the errors were into flexion (underestimation) while 60% were into extension (overestimation).

Table 2 (Cont.). Summary table of the included studies in the systematic review with main findings.

Autor (year)	Sample	Muscle Fatigue Protocol	Instruments/Outcomes	Results
Da Silva, Colson, et al. (2022)	12 healthy physically active individuals: 8M (26.1 ± 4.4 years) 4F (24.0 ± 1.4 years)	Unilateral sets of 15 submaximal knee eccentric contractions of the right lower limb (70% of the maximal voluntary eccentric contraction) at 30°/s, until a 20% decrease in MVIC.	<u>Kinesthesia:</u> - initial position: 30° of KF - direction: to knee flexion and extension at 0.25°/s - instrument: isokinetic dynamometer - outcomes: TTDPM of the right knee	TTDPM significantly increased post-fatigue compared to pre-fatigue, independently of the tested direction ($p<0.05$). TTDPM values were no longer different from pre-fatigue after 24h or 48h ($p>0.84$).
Da Silva, Monjo, et al. (2022)	16 healthy university students (M) (23.1 ± 3.7 years)	Consecutive sets of 5 unilateral knee eccentric contractions at 80% of 1RM, until reaching a 20% decrease in MVIC force.	<u>Joint-Position Sense:</u> - active/contralateral repositioning; OKC - initial position: seated position (extension test: 90° of KF); prone position (flexion test: 0° of KF) - target position: 40° and 70° of KF - instrument: video camera - outcomes: RAE (reference limb angle minus the indicator limb angle)	RAE did not significantly change post-fatigue for the 70° angle in both seated and prone tests ($p>0.22$). For the 40° angle, RAE increased post-fatigue only in the seated test ($p<0.01$) with participants adopting a more flexed position with the indicator limb (fatigued limb) compared to the reference limb (non-fatigued limb). 24h post-fatigue, knee JPS was no longer altered in the seated test ($p>0.92$), but significant delayed RAE were detected in the prone position test ($p<0.01$), also with participants adopting a more flexed position of the indicator limb compared to the reference limb (underestimation).
Da Silva et al. (2021)	13 healthy and physically active individuals (9M; 4F) (25.3 ± 3.6 years)	Unilateral sets of 15 submaximal knee eccentric contractions of the right lower limb (70% of the maximal voluntary eccentric contraction) at 30°/s, until reaching a 20% decrease in MVIC.	<u>Joint-Position Sense:</u> - active/contralateral repositioning; OKC - initial position: 5° of KF - target position: 30° and 70° of KF - instrument: digital inclinometer and isokinetic dynamometer - outcomes: RAE (difference between the reference and the indicator leg)	RAE significantly increased post-fatigue in the 70° angle ($p=0.017$), while no significant effect was seen at 30° ($p=0.43$). Post-fatigue, participants adopted a more extended position with the fatigued indicator limb compared with pre-fatigue ($p=0.03$).

Table 2 (Cont.). Summary table of the included studies in the systematic review with main findings.

Autor (year)	Sample	Muscle Fatigue Protocol	Instruments/Outcomes	Results
Dieling et al. (2014)	26 healthy individuals (7M; 19F): - n = 13 ballet dancers (27.5 ± 6.8 years) - n = 13 non-ballet dancers (25.7 ± 3.7 years)	40 isokinetic knee flexion and extension reps at 180°/s.	<u>Joint-Position Sense:</u> - passive repositioning; OKC - initial position: not described - target position: 30°/45°/60° of KF - instrument: isokinetic dynamometer - outcomes: AAE of the right lower limb	Regarding JPS, AAE did not change ($p=0.629$) in both groups, nor were found significant differences between dancers and non-dancers post-fatigue ($p=0.364$).
			<u>Kinesthesia:</u> - initial position: 30°/45° of KF - direction: to knee extension at 0.25°/s - instrument: isokinetic dynamometer - outcomes: TTDPM of the right lower limb	Regarding kinesthesia, TTDPM significantly increased post-fatigue in the non-dancers ($p=0.030$), while ballet dancers presented no changes ($p=0.585$). No significant differences between dancers and non-dancers were found ($p=0.322$).
Draz et al. (2014)	100 healthy physical therapy students of both sexes (19.18 ± 0.7 years)	Repeated maximal isokinetic lumbar flexions and extensions at 60°/s, until the lumbar extension PT dropped below 50% for 3 consecutive repetitions.	<u>Joint-Position Sense:</u> - active repositioning; OKC - initial position: 90° of KF - target position: 45° of KF - instrument: isokinetic dynamometer -outcomes: AAE of the DL	AAE significantly increased after lumbar paraspinal fatigue ($p=0.0001$).

Table 2 (Cont.). Summary table of the included studies in the systematic review with main findings.

Autor (year)	Sample	Muscle Fatigue Protocol	Instruments/Outcomes	Results
Gear (2004)	20 healthy collegiate soccer and basketball players: - 10M (20.8 ± 1.1 years) - 10F (19.5 ± 1.2 years)	Knee flexion/extension concentric isokinetic exercise (10 reps at 90°/s; 15 reps at 180°/s; 20 reps at 240°/s; 25 reps at 300°/s, with a 40s-rest period between sets) until PT fell below 10%, 30%, or 50% of maximum hamstring baseline PT for 3 consecutive reps.	<u>Joint-Position Sense:</u> - active and passive repositioning; OKC - initial position: 90° of KF (passive test; at angular velocities of 60°/s, 90°/s or 120°/s); 60° of KF (active test) - target position: 20° of KF (passive test); 15°, 30° and 45° of KF (active test) - instrument: isokinetic dynamometer - outcomes: AAE of the NDL	Isokinetic exercise to exertion levels of 10%, 30%, and 50% below hamstring PT did not have a significant effect on passive repositioning ability at angular velocities of 60°/s, 90°/s or 120°/s ($p>0.05$). A statistically significant sex effect was found at the angular velocity of 120°/s ($p=0.02$). For the active repositioning test, the exertion levels of 10%, 30%, and 50% also did not have a significant effect on AAE at 15°, 30° or 45° ($p>0.05$), with no sex effect found.
Gear (2011)	18 healthy soccer and basketball players: - 8M (20.88 ± 1.25 years) - 10F (19.50 ± 1.18 years)	Knee flexion/extension isokinetic exercise until torque output was 90%, 70%, or 50% of the hamstring baseline PT for 3 consecutive reps.	<u>Joint-Position Sense:</u> - active repositioning; OKC - initial position: 60° of KF - target position: 15°, 30°, 45° of KF - instrument: isokinetic dynamometer - outcomes: AAE of the NDL	AAE significantly increased following the 90% of hamstring PT measures ($p=0.02$) and 50% of hamstring PT ($p=0.02$). No differences were found between sexes in the 3 assessed angles ($p=0.74$).
Givoni et al. (2007)	18 healthy individuals (4M; 14F): - eccentric exercise group (20.2 ± 1.0 years) - concentric exercise group (20.0 ± 1.8 years)	- <u>eccentric exercise group (EE)</u> : step down a set of stairs (792 steps), 2 steps at a time; - <u>concentric exercise group (CE)</u> : step up a set of stairs (792 steps), 2 steps at a time. All subjects carried a rucksack with a load of 10% of total BW.	<u>Joint-Position Sense:</u> - active/contralateral repositioning; OKC - initial position: 110° of KF - target position: 50°, 70° of KF - instrument: potentiometers - outcomes: RAE (difference between the reference and the indicator leg)	Immediately after EE, subjects showed a 4.8° error between reference and matching legs. Similarly, CE was followed by a matching error of 3.7°. These effects were significant ($p<0.05$). When the exercised leg acted as the indicator, subjects adopted a more extended position (overestimation).

Table 2 (Cont.). Summary table of the included studies in the systematic review with main findings.

Autor (year)	Sample	Muscle Fatigue Protocol	Instruments/Outcomes	Results
Ju et al. (2010)	15 healthy individuals (8M; 7F) (24.4 ± 1.5 years)	Repetitive (60 reps) active (active fatiguing protocol) or passive movement (passive fatiguing protocol) of knee flexion/extension at 120°/s (range between 10° and 100°).	<u>Joint-Position Sense:</u> - active/passive repositioning; OKC - initial position: 90° of KF - target position: 3 random angles between 10°-80° of KF - instrument: electrogoniometer - outcomes: AAE/RAE of the DL	AAE significantly increased after the active fatiguing protocol, both in the active and passive repositioning tests ($p=0.001$), but a significant decrease following the passive protocol was seen, both in active and passive repositioning tests ($p<0.001$). RAE did not significantly change after both protocols or repositioning tests ($p>0.05$).
Kiyama et al. (2014)	18 healthy individuals (24.8 ± 4.8 years)	20s of knee extensor isometric contractions at 45% of the MVIC, repeated until they were not able to contract more than 5s. The maximum number of reps was set to 15.	<u>Force Sense:</u> - target force: 10% and 30% of MVIC to extension - instrument: data acquisition system providing real-time visual feedback - outcomes: force sense error	In the 10% task, force sense error slightly increased post-fatigue, but there was no significant effect ($p=0.418$). In the 30% task, there was a significant increase in force sense error post-fatigue ($p<0.001$).
Lattanzio et al. (1997)	16 healthy individuals: - 8M (23.9 ± 2.85 years) - 8F (22.1 ± 2.3 years)	3 fatigue protocols in a cycle ergometer: a ramp test (RT) to maximal exhaustion; a continuous test (CT) in which participants had to cycle at 80% of VO_{2max} ; and interval test (IT), required the subject to cycle at alternative workloads (120% or 40% VO_{2max}) until exhaustion.	<u>Joint-Position Sense:</u> - active repositioning; CKC - initial position: standing (weight-bearing test) at 35° of KF - target position: ranged from 10° to 60° of KF - instrument: electrogoniometer - outcomes: AAE of the DL	AAE significantly increased after the 3 fatigue protocols (RP: $p<0.01$; CT: $p<0.03$; IT: $p<0.01$). The IT protocol had the largest mean difference between pre- and post-fatigue measures, followed by the RT and CT, however, no significant differences were found between the 3 protocols ($p>0.05$).

Table 2 (Cont.). Summary table of the included studies in the systematic review with main findings.

Autor (year)	Sample	Muscle Fatigue Protocol	Instruments/Outcomes	Results
Marks (1994)	12 healthy sedentary individuals (F) (18-30 years) - n = 6 (EG: fatigue) - n = 6 (CG: no exercise)	20 maximal concentric/eccentric isokinetic quadriceps contractions through a range of 60° (range from 70° to 10°) without pause at 180°/s.	<u>Joint-Position Sense:</u> - active repositioning; OKC - initial position: 90° of KF - target position: random angle between 45° and 75° of KF - instrument: potentiometer - outcomes: AAE/RAE of the DL	RAE significantly increased between pre- and post-fatigue measurements ($p=0.012$).
Marks and Quinney (1993)	16 healthy sedentary individuals (F): - n = 8 (EG: fatigue) (19.7 ± 1.2 years) - n = 8 (CG: no exercise) (22.3 ± 3.1 years)	20 maximal concentric/eccentric isokinetic quadriceps contractions (range from 70° to 10°) without pause at 180°/s.	<u>Joint-Position Sense:</u> - active repositioning; OKC - initial position: 90° of KF - target position: random angle between 45° and 75° of KF - instrument: potentiometer and isokinetic dynamometer - outcomes: AAE/VAE of the DL	AAE and VAE significantly improved in the CG ($p=0.01$; $p=0.05$), while no changes in accuracy were seen in the EG post-fatigue ($p>0.05$).
Miura et al. (2004)	27 healthy individuals (M) (mean age: 22.2 years)	- <u>Localized fatigue protocol</u> - 60 consecutive maximum concentric contractions of the knee extensors and flexors at 120°/s. - <u>General fatigue protocol</u> - 5 min of running at 10 km/h on a treadmill with a 10% uphill grade.	<u>Joint-Position Sense:</u> - active repositioning; OKC - initial position: 90° of KF - target position: random angle between 10° and 80° of KF - instrument: video camera - outcomes: AAE of the DL	After the localized fatigue protocol, AAE did not change compared with pre-fatigue ($p>0.05$). In contrast, AAE significantly increased after the general protocol ($p<0.05$). Significant differences in AAE between localized and general protocols, with the general protocol producing a greater percent change in AAE (general: 57.0%; local: 13.3%) ($p<0.05$).

Table 2 (Cont.). Summary table of the included studies in the systematic review with main findings.

Autor (year)	Sample	Muscle Fatigue Protocol	Instruments/Outcomes	Results
Mohammadi et al. (2013)	50 healthy conscripts (M) divided in 2 groups after 8 weeks of a military course: (21.4 ± 2.3 years) - n = 8 (injured) - n = 42 (not-injured)	8 weeks of military activities (marching, orienteering, drill training, and combat training; average of 25h/week training), plus physical exercises: jogging (10min); timed and distance running (20min); circuit training (10min); weight exercises (20min); push-ups, sit-ups, and pull-ups (20min); and team sports (30min), with 10min-rest for 2h/day.	<u>Joint-Position Sense:</u> - active and passive repositioning; OKC - initial position: 90° of KF - target position: 45° of KF - instrument: isokinetic dynamometer - outcomes: AAE/VAE of the DL	AAE and VAE significantly increased post-exercise in both injured and uninjured groups ($p=0.01$), with the changes in the injured group being significantly greater than in the uninjured group ($p=0.01$).
Niederseer et al. (2014)	18 healthy elite handball players (M) (22.3 ± 4.9 years)	A simulated handball match.	<u>Joint-Position Sense:</u> - active repositioning; OKC - initial position: 90° of KF - target position: random angles of the knee ROM - instrument: gravitation inclinometer - outcomes: AAE of the DL and NDL	AAE did not significantly change after the simulated handball match ($p=0.561$).
Paschalis et al. (2007)	12 healthy non-trained individuals (F) (20 ± 1 years)	5 sets of 15 maximal eccentric contractions of the dominant knee extensors at 60°/s (range between 0° to 90°), with 2 min rest between sets.	<u>Joint-Position Sense:</u> - active repositioning; OKC - initial position: 90° of KF - target position: 45° of KF - instrument: isokinetic dynamometer - outcomes: AAE/RAE of the DL and NDL	AAE and RAE significantly increased immediately post-fatigue, independently of the visual feedback condition ($p<0.05$), while no changes compared with pre-fatigue were observed after 24h, 48h, or 72h ($p>0.05$). Participants adopted a more extended position in both limbs (overestimation).

Table 2 (Cont.). Summary table of the included studies in the systematic review with main findings.

Autor (year)	Sample	Muscle Fatigue Protocol	Instruments/Outcomes	Results
Paschalis et al. (2013)	32 healthy individuals (F): - n = 12 (lean group) (20.2 ± 0.4 years) - n = 12 (overweight group) (20.8 ± 0.3 years) - n = 8 (underweight group) (21.4 ± 0.4 years)	5 sets of 15 maximal eccentric contractions of knee extensors at 60°/s (range between 0° to 90°), with 2 min rest between sets.	<u>Joint-Position Sense:</u> - active repositioning; OKC - initial position: 0° - target position: 30°/45°/60° of KF - instrument: isokinetic dynamometer - outcomes: AAE/RAE of the DL	AAE significantly increased in the overweight at 30° and 45° angles, as well as all groups showed an AAE increase at 60° ($p < 0.05$). RAE significantly changed at 30° angle for the overweight and underweight, at 45° for the lean and overweight groups ($p < 0.05$), while no changes were found in any group at 60° ($p > 0.05$). For all groups, subjects adopted a more extended position.
Paschalis et al. (2010)	12 healthy individuals undertaking low-intensity leisure activities (M) (23 ± 1 years)	5 sets of 15 eccentric maximal voluntary contractions of the knee flexors at 60°/s, with a 2-minute rest between sets	<u>Joint-Position Sense:</u> - active repositioning; OKC - initial position: 90° of KF - target position: 30°/45°/60° of KF - instrument: isokinetic dynamometer - outcomes: AAE/RAE of the DL	AAE significantly increased post-fatigue in the 3 angles ($p < 0.05$). RAE significantly changed ($p = 0.017$), with participants adopting a more extended position.
Ribeiro et al. (2007)	16 healthy older individuals (M) (69.81 ± 3.92 years)	30 maximum concentric reps of the knee extensors and flexors at 120°/s.	<u>Joint-Position Sense:</u> - active repositioning; OKC - initial position: 90° of KF - target position: random angle 40°-60° of KF - instrument: video camera - outcomes: AAE/RAE/VAE of the DL	AAE and RAE significantly increased post-fatigue ($p < 0.05$). RAE showed directional bias to extension (overestimation), which was exacerbated post-fatigue. VAE did not change from pre- to post-fatigue ($p > 0.05$).

Table 2 (Cont.). Summary table of the included studies in the systematic review with main findings.

Autor (year)	Sample	Muscle Fatigue Protocol	Instruments/Outcomes	Results
Ribeiro et al. (2008)	17 healthy elite volleyball players (F) (18.9 ± 4.2 years)	A simulated volleyball match of 5 sets to mimic competition activity.	<u>Joint-Position Sense:</u> - active repositioning; OKC - initial position: 90° of KF - target position: random angle 40°-60° of KF - instrument: video camera - outcomes: AAE/RAE/VAE of the DL	AAE and RAE significantly increased after the simulated volleyball match ($p<0.01$), evidencing directional bias in the direction of extension (overestimation). VAE did not change from pre- to post-fatigue ($p>0.05$).
Ribeiro et al. (2011)	40 healthy university students (M) (22.1 ± 3.0 years)	Two exercise protocols consisting of 30 consecutive maximal concentric/eccentric contractions of the knee extensors (extensors fatigue protocol) or flexors (flexors fatigue protocol) at 180°/s.	<u>Joint-Position Sense:</u> - active repositioning; OKC - initial position: 90° of KF - target position: 60° of KF - instrument: isokinetic dynamometer - outcomes: AAE/RAE of the DL	AAE significantly increased after extensors and flexors fatigue ($p<0.001$), and no differences were detected between protocols ($p=0.855$). RAE did not change after the extensors ($p=0.563$) or the flexors fatigue ($p=0.753$), also with no differences between protocols ($p=0.526$).
Roberts et al. (2003)	24 healthy university students (mean age: 24 years)	Cycling on an ergometer bicycle until the pulse rate reached a steady state level and subjects reached a score of 14 to 17 on Borg's scale.	<u>Kinesthesia:</u> - initial position: 20°/40° of KF - direction: to knee flexion or extension at 0.5°/s - instrument: a self-designed device - outcomes: TTDPM of the DL and NDL	TTDPM did not change post-fatigue in the assessments toward extension from 20° ($p=0.398$) or 40° ($p=0.125$). Toward flexion, significantly higher TTDPM values were found post-fatigue from 20° ($p=0.025$) and 40° ($p=0.003$).

Table 2 (Cont.). Summary table of the included studies in the systematic review with main findings.

Autor (year)	Sample	Muscle Fatigue Protocol	Instruments/Outcomes	Results
Romero-Franco and Jiménez-Reyes (2017)	32 healthy sprinters (M): - n = 16 (CG: rest) (24.7 ± 3.4 years) - n = 16 (PG: plyometric exercise protocol) (25.0 ± 3.6 years)	High-intensity plyometric exercise protocol consisting of 10 sets of 15 jumps with 45s of recovery between sets.	<u>Joint-Position Sense:</u> - active repositioning; CKC - initial position: standing (weight-bearing test) - target position: 50° of KF - instrument: video camera - outcomes: AAE/RAE/VAE of the DL	AAE did not show differences between pre- to post-fatigue or between groups ($p>0.05$). After the plyometric protocol, RAE ($p=0.001$) and VAE ($p=0.040$) worsened compared to the CG. 5 minutes later, RAE continued to be impaired ($p=0.003$).
Salgado et al. (2015)	14 healthy semi-professional soccer players (M) (25.9 ± 4.6 years)	Official 90-minute soccer match.	<u>Joint-Position Sense:</u> - active repositioning; OKC - initial position: 90° of KF - target position: random angle 40°-60° of KF - instrument: video camera - outcomes: AAE/RAE/VAE of the DL	AAE and RAE significantly increased after the match ($p=0.001$). RAE showed directional bias to flexion (underestimation), which was exacerbated post-fatigue. VAE did not change between pre- and post-fatigue ($p>0.05$).
Shokri et al. (2018)	20 healthy individuals (F) (20.45 ± 1.36 years)	- <u>Concentric Protocol</u> : repeated concentric flexion/extension contractions with the dominant leg at 180°/s until a 50% decline in baseline PT; - <u>Eccentric Protocol</u> : repeated eccentric flexion/extension contractions with the dominant leg at 180°/s until a 50% decline in PT.	<u>Joint-Position Sense:</u> - active repositioning; OKC - initial position: 90° of KF - target position: 45°/60°/75° of KF - instrument: isokinetic dynamometer - outcomes: AAE of the DL <u>Force Sense:</u> - target force: not described - instrument: isokinetic dynamometer - outcomes: Force Sense error	AAE significantly decreased after the concentric protocol ($p=0.028$), but significantly increased after the eccentric protocol ($p=0.001$). Force sense error did not change after the concentric protocol ($p=0.799$), but significantly increased after the eccentric protocol ($p=0.025$).

Table 2 (Cont.). Summary table of the included studies in the systematic review with main findings.

Autor (year)	Sample	Muscle Fatigue Protocol	Instruments/Outcomes	Results
Skinner et al. (1986)	11 healthy individuals attending the Navy SEAL team training (M) (mean age 22.8 years)	Sprinting alternate 1-mile and 1/4-mile intervals with a 90s-rest between each interval for a total running distance of 3 ³ / ₄ miles, plus walking on a treadmill for 2 minutes at a 7mph rate with a 15% uphill grade, followed by a 90s-rest and a second treadmill session.	<u>Joint-Position Sense:</u> - active repositioning; OKC - initial position: 90° of KF - target position: 25° of KF - instrument: a self-designed device - outcomes: AAE of the DL	AAE significantly increased post-fatigue ($p<0.045$). TTDPM showed no significant changes post-fatigue ($p>0.05$), although the mean angle was less post-fatigue than pre-fatigue.
			<u>Kinesthesia:</u> - initial position: 60° of KF - direction: to knee extension at 0.5°/s - instrument: a self-designed device - outcomes: TTDPM of the DL	
Torres et al. (2010)	14 healthy individuals (M) (22.1 ± 2.1 years)	Sets of 30 eccentric quadriceps contractions at 60°/s at a target of 60% of the maximal concentric PT until exhaustion (range between 20° and 100° of KF); the exercise was interrupted whenever subjects could not complete 2 sets.	<u>Joint-Position Sense:</u> - active repositioning; OKC - initial position: 100° of KF - target position: 30°/70° of KF - instrument: isokinetic dynamometer - outcomes: AAE of the DL	AAE significantly increased 1h post-fatigue in both 30° and 70° angles, and remained significantly increased until 48h after ($p<0.05$), with no differences being reported in accuracy between angles ($p>0.05$). TTDPM significantly increased 1h post-fatigue in both 30° and 70° angles, and remained significantly increased after 24h only at the 70° angle ($p>0.05$), with TTDPM values being significantly higher at this time-point in the 70° angle compared with the 30° angle ($p>0.05$). Force sense error significantly increased 1h after exercise and remained increased until 48h ($p<0.05$).
			<u>Kinesthesia:</u> - initial position: 30°/70° of KF - direction: to knee extension at 0.25°/s - instrument: isokinetic dynamometer - outcomes: TTDPM of the DL	
			<u>Force Sense:</u> - target force: 20% of MCPT to extension - instrument: isokinetic dynamometer - outcomes: Force Sense error	

Table 2 (Cont.). Summary table of the included studies in the systematic review with main findings.

Autor (year)	Sample	Muscle Fatigue Protocol	Instruments/Outcomes	Results
Vila-Chã et al. (2011)	25 healthy individuals (14M; 11F) - n = 10 (CG: no exercise) (25.0 ± 3.6 years) - n = 15 (EG: eccentric exercise) (22.0 ± 0.8 years)	4 sets of 25 maximum voluntary eccentric knee extension contractions at 60°/s (range between 10° to 90° of KF), with a 3-minute rest between sets.	<u>Joint-Position Sense:</u> - active repositioning; OKC/CKC - initial position: 90° of KF (OKC)/ 0° of KF (CKC) - target position: 30°/60° of KF - instrument: electrogoniometer - outcomes: AAE/RAE/VAE of the right knee	In the OKC task, AAE and RAE significantly increased only at 60° immediately post-fatigue ($p<0.05$), and remained increased after 24h ($p<0.05$). Participants adopted a more extended position (overestimation). Both AAE and RAE were different between angles ($p<0.001$), with errors at 30° being smaller than at 60°. VAE significantly increased only at 60° and immediately post-fatigue ($p<0.001$). In the CKC task, AAE significantly increased post-fatigue at 60° and 30° ($p<0.01$), and remained increased after 24h ($p<0.05$). Higher AAE and RAE at 60° than at 30° ($p<0.001$). Participants adopted a more extended position. VAE significantly increased only at 60° immediately post-fatigue ($p<0.001$).

1RM: 1 repetition maximum; **AAE:** absolute angular errors; **BW:** body weight; **CG:** control group; **CKC:** closed kinetic chain; **DL:** Dominant Limb; **EG:** experimental group; **F:** Female; **HR:** heart rate; **JPS:** Joint-Position Sense; **KF:** knee flexion; **M:** male; **MCPT:** Maximal Concentric Peak Torque; **MVIC:** maximal voluntary isometric contraction; **NDL:** non-dominant limb; **OA:** osteoarthritis; **OKC:** open kinetic chain; **PG:** Plyometric Group; **PT:** Peak Torque; **RAE:** relative angular errors; **reps:** repetitions; **RMS:** root mean square; **ROM:** range of motion; **TTDPM:** threshold to detect passive motion; **VAE:** variable angular errors.

Discussion

This systematic review aimed to summarise the evidence about the effect of muscle fatigue on the knee proprioception of trained and non-trained individuals.

Overall, a high heterogeneity was observed between the included studies regarding the protocols used to induce muscle fatigue, as well as the methodologies carried out to assess the subcomponents of knee proprioception.

Effect of muscle fatigue on the knee joint-position sense

According to previous investigations, peripheral muscle fatigue, as it occurs within the muscle, leads to metabolic changes that affect the muscle spindle function, increasing its discharge threshold, which can compromise proprioceptive input and impair position matching (Balestra et al., 1992; Gribble & Hertel, 2004; Pedersen et al., 1998; Voight et al., 1996).

An investigation from Skinner et al. (1986) revealed that the reproduction of a knee joint angle is more sensitive to muscle fatigue than, for example, kinesthesia. Indeed, most of the included studies investigated the effect of either a local or general fatigue protocol on the knee JPS.

Regarding trained individuals, the studies of Salgado et al. (2015), Ribeiro et al. (2008), and Niederseer et al. (2014) induced fatigue through a soccer, volleyball, and handball match, respectively. Both in Salgado et al. (2015) and Ribeiro et al. (2008) investigations, the knee JPS of the soccer and volleyball players decreased significantly after the matches. Regarding the study of Niederseer et al. (2014), the handball match did not produce any effects on the knee JPS, wherein the authors admitted that the intensity of the simulated match might not have been enough to affect proprioceptive acuity.

The study of Azevedo et al. (2018), also in soccer players, reported opposite results compared to Salgado et al. (2015), since no significant increases in the repositioning errors were reported after fatigue. Although the knee JPS assessment methods were similar (open kinetic chain technique and active

repositioning method from a passive positioning), some aspects should be recognised. First, the fatigue protocols were distinct, as in the investigation of Azevedo et al. (2018), muscle fatigue was induced locally by a repetitive sit-to-stand task, while Salgado et al. (2015) induced a more general fatigue with the 90-minute soccer match. Indeed, Miura et al. (2004) compared the effect of a localized and general fatigue protocol on the knee JPS, reporting a significant increase in the repositioning errors only after the general protocol. Although localized fatigue can cause a dysfunction in the muscle spindle, these authors hypothesized that the general fatigue protocol may have affected other mechanisms of the proprioceptive pathway that caused central fatigue, which might have led to deficits in the central processing of the proprioceptive input. Second, the fatigue protocol of Azevedo et al. (2018) was probably not effective enough to induce a real fatigued state, which indeed was not confirmed by objective measures. Another discrepancy between the studies was regarding the directional bias in which the soccer players failed the target angles. In Azevedo et al. (2018), the players failed the angles in the direction of extension (overestimation), while in Salgado et al. (2015), directional bias was to flexion (underestimation). Ribeiro et al. (2008) also reported the relative angular errors after the volleyball match, and contrary to Salgado et al. (2015), revealed a directional bias in the direction of extension (overestimation). These findings suggest that different fatigue protocols may induce different information in the muscle spindle about the muscle's stretch position.

The study of Carrasco et al. (2021) in semi-professional soccer players submitted the participants to a localized and a general fatigue protocol, where both protocols caused significant increases in absolute angular errors, without differences reported between them. These results are not in line with the previously mentioned study of Miura et al. (2004), as only after the general protocol a significant decrease in position matching was observed. Nevertheless, it is proposed that exertional protocols, even though they are local, can also induce central fatigue, decreasing motor control precision and movement proficiency, which might explain the absence of differences between the local and general protocols of the study of Carrasco et al. (2021).

Another study in soccer and basketball players (Gear, 2011) investigated the role of different levels of fatigue on the knee JPS. Participants performed a knee flexion/extension isokinetic exercise until torque output was 90%, 70%, or 50% of the baseline peak torque. Results revealed significant differences between pre-fatigue and following the 90% and 50% protocols, suggesting that fatigue may have an influence on the knee proprioception after mild or maximum fatigue.

Romero-Franco and Jiménez-Reyes (2017) studied the effect of a high-intensity plyometric exercise protocol in sprinters and reported a significant worsening of relative and variable angular errors immediately after, while relative errors remained impaired after 5 minutes.

Mohammadi et al. (2013) evaluated whether military physical exercises alter knee JPS and examined the relation of JPS to lower limb injuries in military service. Knee proprioception significantly decreased in the injured and non-injured participants during the 8-week program, with the conscripts who suffered lower limb injuries presenting worse JPS than those who did not suffer injuries.

In the included studies, eccentric-fatigue protocols seemed to worsen knee JPS. Bottoni et al. (2015) aimed to investigate the effect of uphill (concentric exercise) and downhill walking (eccentric exercise) on the knee JPS and revealed that after downhill walking, JPS was significantly worse than pre-fatigue, while after uphill walking, no differences were observed. The authors hypothesized that the worsening in JPS was caused by damage to the muscle fibres due to eccentric exercise, altering lactic acid concentration, temperature, and pH, which consequently led to deficits in the input from muscle mechanoreceptors. Effectively, this assumption is in line with Sonkodi et al. (2022), whose results found a delay in the medium-latency response of the quadriceps muscle after a delayed-onset muscle soreness (DOMS) exercise protocol, which was attributed to a proprioceptive type Ia afferent microdamage in the muscle spindle. Similarly, Givoni et al. (2007) compared the effect of stepping down a set of stairs (eccentric exercise) or stepping up them (concentric exercise) on position matching. The authors found an immediate increase in repositioning errors after the eccentric exercise of 4.8° and of 3.7° after the concentric exercise. Also, Shokri et al. (2018)

found a significant increase in repositioning errors after an eccentric flexion/extension protocol, while a significant decrease in errors was noted after a concentric protocol. Likewise, the study of Vila-Chã et al. (2011) investigated the effects of a quadriceps eccentric exercise on the knee JPS in weight-bearing and non-weight-bearing assessments and reported that the protocol impaired proprioception both immediately after and 24 hours after exercise, only in the non-weight-bearing assessments. The authors hypothesized that additional proprioceptive input may have come from compression of the foot plant or from the contraction of other non-affected muscle groups by fatigue, which led to an unaffected matching position in the weight-bearing assessment. Additional evidence regarding a deleterious effect of eccentric protocols was also demonstrated in the studies of Da Silva, Monjo, et al. (2022) and Paschalis et al. (2010). Despite this evidence, a recent review also assumes that eccentric exercise, as well as metabolic products, may not contribute to repositioning errors (Proske, 2019).

Regarding concentric fatigue protocols, Allen et al. (2010) found significant increases in relative angular errors after a concentric protocol for the knee flexors. Contrary to these findings, Bersotti et al. (2022) reported no significant differences between pre- and post-fatigue errors after a concentric protocol of the knee extensors. These conflicting results suggest that muscle fatigue induced using a concentric protocol may affect the repositionings to extension more when the knee flexors are fatigued, probably related to the muscle spindles' function of detecting muscle stretch (Lephart et al., 1998). Indeed, while repositioning to extension, a stretching of the knee flexors is performed, which can compromise accuracy when this muscle group is fatigued. Nevertheless, the investigation of Ribeiro et al. (2011) does not support the previous suggestion, as fatigue was induced at separate times in the knee extensors and flexors. However, both protocols significantly increased repositioning errors, concluding that, regardless of the fatigued muscle group, fatigue reduced knee accuracy while repositioning to extension. However, these comparisons should be interpreted with caution since Ribeiro et al. (2011) induced fatigue through concentric and eccentric

contractions, while the studies of Allen et al. (2010) and Bersotti et al. (2022) were strictly concentric.

Lattanzio et al. (1997) investigated the effect of three different fatigue protocols on the knee JPS of healthy individuals involved in moderate or greater intensity exercise. All three protocols were performed in a cycle ergometer: a ramp test to maximal exhaustion; a continuous test of cycling at 80% of $\text{VO}_{2\text{max}}$; and an interval test that required participants to cycle at alternative workloads (40% or 120% of $\text{VO}_{2\text{max}}$). A significant increase in repositioning errors was reported after all protocols, wherein the largest mean difference between pre- and post-fatigue was found in the interval protocol, followed by the ramp test and, finally, by the continuous test. However, it should be noted that there were no significant differences between protocols.

Regarding non-trained individuals, Azevedo et al. (2018) and Ali et al. (2013) assessed the ability to reproduce the angles of 20° and 45° of knee flexion through active repositioning after a local (Azevedo et al., 2018) or a general fatigue protocol (Ali et al., 2013). Both studies found a significant increase in repositioning errors only at the angle of 45° , suggesting that muscle mechanoreceptors were more affected by fatigue, since this is an intermediate angle of the knee ROM, where this type of mechanoreceptors are more active (Olsson et al., 2004). Similar results were reported by Da Silva et al. (2021), as fatigue only affected the repositioning at 70° , while no effects were seen at 30° . In line with these studies, a significant worsening of JPS was also recorded in other studies after fatigue while repositioning to intermediate angles in sedentary individuals (Marks, 1994) and in healthy subjects (Bazneshin et al., 2015), confirming that fatigue affected the integrity of muscle mechanoreceptors.

In the study of Paschalis et al. (2007), with healthy non-trained individuals, repositioning errors significantly increased after an eccentric fatigue protocol targeting the knee extensors. However, JPS did not remain impaired after 24, 48, or 72 hours. On the contrary, in the study of Torres et al. (2010), repositioning errors significantly increased one hour after an eccentric quadriceps fatigue protocol, but remained increased after 48 hours. It is important to note that the

protocol of Torres et al. (2010) consisted of sets of 30 eccentric quadriceps contractions, while the protocol of Paschalis et al. (2007) consisted of sets of only 15 contractions, which may explain why the participants of Torres et al. (2010) saw their JPS impaired for a longer period.

In the study of Changela et al. (2013) in physiotherapy students, an increase of the repositioning errors after fatigue was revealed, even though the assessed target angle was an extreme angle of the knee ROM, which according to Riemann and Lephart (2002), corresponds to a position where joint mechanoreceptors are more stimulated. Indeed, after exercise, it is expected that fatigue affects more the muscle. However, ligaments and capsular structures can also experience changes (Skinner et al., 1986). In fact, previous investigations showed knee ligament laxity as a result of exercise (Johannsen et al., 1989; Steiner et al., 1986), which might explain why, in extreme ranges, muscle fatigue also can impair JPS by disturbing input from these receptors. Furthermore, according to previous investigations, muscle mechanoreceptors, particularly muscle spindles, are capable of providing afferent information across the entire physiological ROM (Lephart et al., 2000; Proske & Gandevia, 2012), which is another explanation for the significant worsening of position matching in extreme ranges.

The study of Ju et al. (2010) proposed to examine the effects of fatiguing exercises (repetitive active movement and repetitive passive movements) on the active and passive repositioning accuracy. Results showed a significant increase in repositioning errors following repetitive active movement, but an improvement following repetitive passive movement intervention, having hypothesized that the last one induced a warm-up effect, thereby increasing the sensitivity of mechanoreceptors around the knee.

In older individuals, Ribeiro et al. (2007) submitted the participants to a local concentric fatigue protocol of the knee extensors and flexors, revealing a significant increase in repositioning errors. Although evidence suggests that aging causes a decline in proprioception both at the central and peripheral level (Ribeiro et al., 2007), results regarding the effect of fatigue on young subjects seem similar in older individuals. Therefore, it would be important to investigate

the effect of the same protocol on the repositioning errors of both young and older individuals to verify if the impact of the protocol is similar in older participants due to the normal age-associated decline.

Although most of the evidence is that muscle fatigue decreases knee JPS, there are also studies contradicting these findings. Dieling et al. (2014) did not report significant increases in repositioning errors in both dancers and in non-dancers after performing an isokinetic knee flexion and extension fatigue protocol. However, it should be noted that the authors used a passive repositioning method, which, according to Proske et al. (2000), leads to a lower activation of muscle mechanoreceptors, which may explain the absence of effects after fatigue. Also, Marks and Quinney (1993) stated no effects of a concentric/eccentric quadriceps protocol on the knee JPS of sedentary individuals, despite an active repositioning being performed to intermediate ranges.

Bozkurt et al. (2020) included patients with knee osteoarthritis and healthy post-menopausal women, submitting them to an eccentric protocol of the knee extensors and flexors. Results demonstrated a significant increase in repositioning errors in both groups after the protocol. The authors also found higher errors in the osteoarthritic patients in the pre- and post-fatigue measurements compared to the healthy participants, which may be related to joint deterioration by osteoarthritis and, consequently, lead to the impairment of joint mechanoreceptors.

On the contrary, Bayramoglu et al. (2007) did not demonstrate that muscle fatigue affected the knee JPS of patients with bilateral knee osteoarthritis or the healthy age-matched volunteers, nor did they report differences in the accuracy between groups. However, the methodology used by the authors raises some issues. First, the fatigue protocol was of moderate intensity (5 minutes on a cycle ergometer), which may not have been enough to cause effective muscle fatigue. Second, it was used an unusual assessment of proprioception, consisting of an intermediate method of assessing JPS and kinesthesia, in which the leg was passively moved from flexion to extension, and vice versa at 5°/s, and participants had to press a

button when they thought the leg was passing the target position of 45° of flexion. This methodology presents two problems: the first is that the speed at which the passive movement was performed was too high, since, according to the recommendations of Lephart et al. (1998), the assessment of JPS through passive repositioning should be conducted at slow angular velocities between 0.5 - 2°/s; and second, it is not very clear that the method used is an intermediate method of assessing the JPS and kinesthesia components, resembling something more like the JPS assessment through passive repositioning. The authors reported that the reliability of the method was not excellent, but only fair to good.

In the study of Draz et al. (2014), it was shown that the knee JPS assessed at 45° of knee flexion significantly worsened after fatiguing exercise of the lumbar paraspinal muscles. The authors proposed that changes in the afferent information from mechanoreceptors of the lumbar spine after fatigue may have also impaired quadriceps motor neuron excitability. Fatigue is known to cause difficulty in maintaining adequate trunk stability, which may also affect lower limb joints. This may explain the increased risk of lower limb injury in people with poor core and trunk stability (Hart et al., 2009).

Some studies also compared the accuracy in extreme and intermediate angles. Azevedo et al. (2018), Vila-Chã et al. (2011), and Cowan (2009) reported better accuracy in extreme angles when compared to intermediate angles of the knee ROM. Indeed, proprioception has been defined as the cumulative sensory input to the Central Nervous System (CNS) (Lee & Chow, 2013), meaning that, at extreme ranges, there is a contribution from joint mechanoreceptors, but also a contribution from muscle spindles is present, as they can provide information about position through the entire ROM. In that sense, a better proprioceptive accuracy is expected in extreme ranges. On the contrary, in intermediate ranges, the stimulated mechanoreceptors are only the muscular, producing worse repositioning errors in those ranges (Proske & Gandevia, 2012; Riemann & Lephart, 2002).

Regarding the influence of sex, both Azevedo et al. (2018) and Gear (2004) showed no significant differences between male and female participants, which is in line with other investigations (Azevedo et al., 2021; Ghiasi & Akbari, 2007; Nitsure & Prabhu, 2015).

Finally, Paschalis et al. (2013) investigated the effect of BMI on the knee JPS after an eccentric fatigue protocol. Participants were divided into three BMI categories: underweight, lean, and overweight. Results revealed that fatigue affected more the knee JPS of the overweight and underweight compared with the lean group. It was proposed that overweight subjects show a higher sedentary behaviour and less activity in eccentric daily activities, such as descending stairs or taking walks with downhill inclinations. In that sense, these subjects may be more susceptible to muscle damage when submitted to an eccentric fatigue protocol, which can explain the worse accuracy in this group. Regarding the underweight individuals, decreased muscle mass can be identified as a factor for lower recruitment of muscle mechanoreceptors, impairing proprioceptive input.

Effect of muscle fatigue on the knee kinesthesia

According to Barrett et al. (1991) and Lephart et al. (1997), passive tests (e.g., kinesthesia and JPS through passive repositioning) are mostly used to assess the integrity of joint mechanoreceptors. However, it is important to note that muscle mechanoreceptors' contribution cannot be disregarded, as joint mechanoreceptors' activity cannot be isolated in passive tests, nor can the muscle mechanoreceptors' activity be isolated in active tests. Indeed, there are important variables to consider regarding receptors' activation, such as, for example, the arc of motion. As previously described, joint mechanoreceptors are more active near the end ranges, while muscle ones are more active in intermediate ranges (Docherty et al., 1998; Riemann & Lephart, 2002).

Following the assumption that kinesthesia is typically used to assess the integrity of joint mechanoreceptors, it would be logical to measure the TTDPM from extreme angles of the knee ROM. Indeed, three studies considered the 20°

(Allison, Abt, et al., 2016; Roberts et al., 2003) and 30° of knee flexion (Da Silva, Colson, et al., 2022; Dieling et al., 2014; Torres et al., 2010). However, other four investigations considered intermediate angles like 40° (Roberts et al., 2003); 45° (Dieling et al., 2014), 60° (Skinner et al., 1986), and 70° of knee flexion (Torres et al., 2010).

Another important factor for receptors' activation is the angular velocity at which the assessment is conducted. According to Lephart et al. (1998), to minimise the contribution of muscle mechanoreceptors in passive tests, angular velocities between 0.5°/s and 2°/s should be chosen, as these are thought to selectively target the slow-adapting Ruffini or Golgi mechanoreceptors found in the ligamentous and capsular tissues of the knee (Riemann & Lephart, 2002), while faster velocities (e.g. 5°/s) target mostly muscle mechanoreceptors. Indeed, in all six studies in which kinesthesia was assessed, the tests were performed at 0.25°/s or 0.5°/s.

In the study of Allison, Abt, et al. (2016), a general protocol was chosen to simulate fatigue mechanisms experienced in game/practice situations, and fatigue was monitored during the protocol with participants reporting near maximum levels of perceived exertion and reaching maximal blood lactate concentration, according to the authors. However, no effect on TTDPM was reported after this protocol, either to knee flexion or extension from a 20° of knee flexion position, which might suggest that muscle fatigue did not impair joint mechanoreceptors. Consequently, no dysfunction of the central pathways to motor control was induced.

In the study of Roberts et al. (2003), healthy university students were asked to estimate the TTDPM from starting positions of 20° and 40° of knee flexion before and after a cycling fatigue protocol. These authors also reported no significant differences post-fatigue on the knee kinesthesia towards extension in both angles.

Also, Skinner et al. (1986) found no significant changes in TTDPM values after a sprinting and running fatigue protocol in Navy SEALs, from an initial test position of 60° of knee flexion towards extension. The authors even reported that TTDPM

seemed to improve after fatigue, although the difference underpinning this assumption was not significant.

Both Skinner et al. (1986) and Allison, Abt, et al. (2016) hypothesize that since muscle fatigue would most likely impair muscle mechanoreceptors of the knee joint, enhanced sensitivity of joint mechanoreceptors within the ligamentous and capsule structures may arise in response. This may explain the absence of affectation of knee kinesthesia following muscle fatigue in either extreme or intermediate ranges, which may be an important protective mechanism of compensation to assure knee joint stability. The fact that Skinner et al. (1986) reported better values after inducing fatigue might reinforce this suggestion.

However, in the study of Roberts et al. (2003), an assessment to knee flexion was also conducted, but this time, significantly higher TTDPM values after fatigue were found from both 20° and 40° angles. The authors considered that the cycling protocol fatigued more the quadriceps than the hamstrings, and considering that muscle spindles signal muscle stretching (Riemann & Lephart, 2002) and the test was conducted towards flexion by stretching the quadriceps, the assessment to flexion revealed a more impaired function of quadriceps after the fatigue protocol compared to the hamstrings. Therefore, the results of this study do not support the hypothesis raised by Skinner et al. (1986) and Allison, Abt, et al. (2016), since effectively, at least for the test towards flexion, it does not seem to have occurred compensation by the joint mechanoreceptors to counterbalance the effects of fatigue on muscle ones.

Contrary to the previous studies' findings towards extension, the local eccentric fatigue protocol of Torres et al. (2010) caused a significant decline in kinesthesia, considering initial positions of 30° and 70° of knee flexion. This decline was seen one hour after fatigue in both angles, and remained until 24 hours after the protocol, only for the 70° angle, suggesting that the protocol affected both joint and muscle mechanoreceptors, but the impairment was longer in the muscle ones. Furthermore, the authors registered higher TTDPM values in the intermediate angle of 70° compared to the extreme of 30°, suggesting that muscle mechanoreceptors were more affected by fatigue than joint mechanoreceptors.

Similar results were found by Da Silva, Colson, et al. (2022), also after a local eccentric fatigue protocol. These authors reported significant increases in TTDPM after fatigue in an assessment from 30° of knee flexion to both knee flexion and extension, and just like Torres et al. (2010), TTDPM values at this angle were no longer different from baseline values after 24 or 48 hours.

Finally, Dieling et al. (2014) evaluated the effect of a local knee flexion/extension fatigue protocol on the knee kinesthesia of ballet dancers and non-dancers, and found that TTDPM only increased in the non-dancers. The authors explained that the ballet dancers have been practicing for over 10 years, which suggests that these individuals have possibly developed greater resistance to muscle fatigue on proprioceptive acuity. Furthermore, in addition to involving extreme coordination of movements, ballet training times are long, and the dancers are used to training under fatiguing conditions.

An interesting interpretation of the previous investigations can be drawn. Kinesthesia accuracy seems to be related to the type of fatigue protocol, since after local protocols (Da Silva et al., 2021; Dieling et al., 2014; Torres et al., 2010), TTDPM values significantly increased, while no changes were observed after more general protocols (Allison, Abt, et al., 2016; Roberts et al., 2003; Skinner et al., 1986).

Effect of muscle fatigue on the knee force sense

According to Riemann et al. (2002), force sense tests aim to assess the integrity of muscle mechanoreceptors at specific efforts. Neural information related to force sense includes signals from mechanoreceptors in muscles and tendons, and the sense of effort produced by the CNS (Hassanlouei et al., 2012).

Force sense has an important role in maintaining joint stability and decreasing the risk of knee injury since it represents the ability to produce appropriate force in relevant activities to sports, such as jumping or cutting (Allison, Sell, et al., 2016). In this sense, four of the included studies assessed the effect of muscle

fatigue on the ability to reproduce a target force at the knee (Allison, Sell, et al., 2016; Kiyama et al., 2014; Shokri et al., 2018; Torres et al., 2010).

In the study of Allison, Sell, et al. (2016), despite the confirmation of fatigue through electromyography (EMG), no significant changes after a concentric fatigue protocol were seen in the ability to reproduce a force target of 15% of the MVIC for extension or flexion. In that sense, the authors concluded that muscle fatigue did not affect the quadriceps or hamstrings' force sense.

In the case of Kiyama et al. (2014), two target loads for extension were used (10% and 30% of the MVIC). Force sense error increased in both loads, although a significant increase was reported only in the 30% load.

Although there was no description of the used target force, Shokri et al. (2018) reported an exacerbation of force sense error after fatigue, which was significantly higher in the eccentric protocol compared to the concentric one.

Finally, Torres et al. (2010) assessed knee force sense for a target force of 20% of the MVIC to extension. After an eccentric fatigue protocol, force sense significantly decreased one hour after exercise, and remained decreased until 48 hours.

Besides the fact that muscle mechanoreceptors' function is affected by fatigue, the CNS can also increase the number of motor units to compensate for the decline of force output after fatigue (Carpentier et al., 2001), which can be confirmed by increased EMG activity, for example as in the study of Kiyama et al. (2014). According to these authors, the increased muscle activation interferes with the estimation of force output. In that sense, it is reasonable to hypothesize that, if loads increase, the difficulty of the reproduction force task also increases. Indeed, the included studies support this, as muscle fatigue protocols seemed not to impair force sense when it was assessed in lower force targets (Allison, Sell, et al., 2016; Kiyama et al., 2014). On the contrary, force sense was significantly affected after fatigue when considering force targets of 20% or more of the MVIC (Kiyama et al., 2014; Torres et al., 2010). Another suggestion when

interpreting these results is that muscle fatigue after eccentric protocols seems to have a greater impact on force sense when compared to concentric protocols.

Limitations

Some limitations of the present systematic review should be recognized. First, according to the MINORS tool, the assessment of the non-randomized included studies revealed that the quality was only fair in all studies. Also, the six studies that were randomized and assessed with the RoB2 tool revealed that four of them had a higher risk of bias, while only two studies were considered to have a low risk of bias. This suggests the need for caution when interpreting these results. Second, only articles published in English, Portuguese, Spanish, Italian, or French were considered, which led to the exclusion of studies in other languages that could have been relevant to the review.

Conclusions

The overall conclusion of the present systematic review is that muscle fatigue has a negative impact on the knee proprioception of trained and non-trained individuals. Specifically for JPS, both localized and generalized fatigue protocols led to a significant increase in repositioning errors. Regarding kinesthesia, it appears to be more affected by localized fatigue protocols, whereas force sense seems to deteriorate particularly after eccentric fatigue protocols and when assessed at higher target forces. This negative impact of muscle fatigue may lead to defective knee stability, leading to an increased risk of injuries.

Future research regarding the effects of muscle fatigue on the knee proprioception should address studies with control groups, with the analysis of the reliability of the assessment methods and that ensure the blinding of participants and investigators.

References

- Ali, Y., Farzaneh, G., & Homayoon, A. (2013). The Effect Of Fatigue On The Ankle And Knee Proprioception And Dynamic Control Of Posture. *International Journal of Sports Sciences & Fitness*, 3(2), 235-249. <https://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=90508075&lang=pt-pt&site=ehost-live&scope=site>
- Allen, T., Leung, M., & Proske, U. (2010). The effect of fatigue from exercise on human limb position sense. *The Journal of physiology*, 588(8), 1369-1377. <https://doi.org/10.1113/jphysiol.2010.187732>
- Allison, K. F., Abt, J. P., Beals, K., Nagle, E. F., Lovalekar, M. T., Lephart, S. M., & Sell, T. C. (2016). Aerobic capacity and isometric knee flexion strength fatigability are related to knee kinesthesia in physically active women. *Isokinetics & Exercise Science*, 24(4), 357-365. <https://doi.org/10.3233/IES-160638>
- Allison, K. F., Sell, T. C., Benjaminse, A., & Lephart, S. M. (2016). Force sense of the knee not affected by fatiguing the knee extensors and flexors [Article]. *Journal of sport rehabilitation*, 25(2), 155-163. <https://doi.org/10.1123/jsr.2014-0298>
- Azevedo, J., Rodrigues, S., & Seixas, A. (2018). *Efeito da sobrecarga muscular aguda e crónica no senso de posição articular do joelho* Universidade Fernando Pessoa]. Porto. <http://hdl.handle.net/10284/7060>
- Azevedo, J., Rodrigues, S., & Seixas, A. (2021). The influence of sports practice, dominance and gender on the knee joint position sense. *The Knee*, 28, 117-123. <https://doi.org/10.1016/j.knee.2020.11.013>
- Balestra, C., Duchateau, J., & Hainaut, K. (1992). Effects of fatigue on the stretch reflex in a human muscle. *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section*, 85(1), 46-52. [https://doi.org/10.1016/0168-5597\(92\)90101-G](https://doi.org/10.1016/0168-5597(92)90101-G)

- Barrett, D. S., Cobb, A. G., & Bentley, G. (1991). Joint proprioception in normal, osteoarthritic and replaced knees. *The Journal of bone and joint surgery. British volume*, 73(1), 53-56. <https://doi.org/10.1302/0301-620X.73B1.1991775>
- Bayramoglu, M., Toprak, R., & Sozay, S. (2007). Effects of osteoarthritis and fatigue on proprioception of the knee joint. *Archives of physical medicine and rehabilitation*, 88(3), 346-350. <https://doi.org/10.1016/j.apmr.2006.12.024>
- Bazneshin, M. M., Amiri, A., Jamshidi, A. A., & Vasaghi-Gharamaleki, B. (2015). Quadriceps muscle fatigue and knee joint position sense in healthy men. *Physical Treatments - Specific Physical Therapy Journal*, 5(2), 109-114. <https://doi.org/10.15412/J.PTJ.07050207>
- Bennell, K., Wee, E., Crossley, K., Stillman, B., & Hodges, P. (2005). Effects of experimentally-induced anterior knee pain on knee joint position sense in healthy individuals. *J. Orthop. Res.*, 23(1), 46-53. <https://doi.org/10.1016/j.orthres.2004.06.008>
- Bersotti, F. M., De Melo, T. B., Rafael Skau, J., Mochizuki, L., & Ervilha, U. F. (2022). Fatigue of knee extensor muscles does not alter knee joint position sense. *J. Mech. Med. Biol.*, 22(2), 2250012-2250011-2250012-2250019. <https://doi.org/10.1142/S0219519422500129>
- Bottoni, G., Heinrich, D., Kofler, P., Hasler, M., & Nachbauer, W. (2015). The Effect of Uphill and Downhill Walking on Joint-Position Sense: A Study on Healthy Knees. *Journal of sport rehabilitation*, 24(4), 349-352. <https://doi.org/10.1123/jsr.2014-0192>
- Bozkurt, S., ÖZer, Ç., Kuzay, D., DemİR, P., & Meray, J. (2020). The Effect of a Single Session of Eccentric Exercise on Proprioception and Oxidative Stress in Knee Osteoarthritis: A Preliminary Study. *Journal of Physical Medicine & Rehabilitation Sciences*, 23(3), 191-200. <https://doi.org/10.31609/jpmrs.2020-74173>

- Carpentier, A., Duchateau, J., & Hainaut, K. (2001). Motor unit behaviour and contractile changes during fatigue in the human first dorsal interosseus. *The Journal of physiology*, 534(3), 903-912. <https://doi.org/10.1111/j.1469-7793.2001.00903.x>
- Carrasco, L., Espinar, J., Carbonell, F. J., & Martínez-Díaz, I. C. (2021). Local and general fatigue: Effects on knee proprioception in soccer players. *Rev.int.med.cienc.act.fís.deporte*, 21(84), 683-698. <https://doi.org/10.15366/rimcafd2021.84.004>
- Changela, P. K., Selvamani, K., & Ramaprabhu. (2013). A Study to Evaluate the effect of Fatigue on Knee Joint Proprioception and Balance in Healthy Individuals. *Indian Journal of Physiotherapy & Occupational Therapy*, 7(1), 213-217. <https://search.ebscohost.com/login.aspx?direct=true&db=rzh&AN=102831572&lang=pt-pt&site=ehost-live&scope=site>
- Cowan, J. (2009). *Effect of fatigue on proprioceptive acuity in the asymptomatic untrained male knee* Unitec New Zealand]. New Zealand. <https://hdl.handle.net/10652/1340>
- Craig, J. C., & Rollman, G. B. (1999). Somesthesia. *Annual Review of Psychology*, 50(1), 305-331. <https://doi.org/10.1146/annurev.psych.50.1.305>
- Da Silva, F., Colson, S. S., Zghal, F., Chorin, F., Guérin, O., & Monjo, F. (2022). Immediate voluntary activation deficits following submaximal eccentric contractions of knee extensors are associated with alterations of the sense of movement. *Scientific Reports*, 12(1), 1-10. <https://doi.org/10.1038/s41598-022-06081-2>
- Da Silva, F., Monjo, F., Gioda, J., Blain, G. M., Pignonier, E., Corcelle, B., & Colson, S. S. (2022). Knee position sense and knee flexor neuromuscular function are similarly altered after two submaximal eccentric bouts. *European journal of applied physiology*. <https://doi.org/10.1007/s00421-022-05063-6>

- Da Silva, F., Monjo, F., Zghal, F., Chorin, F., Guérin, O., & Colson, S. S. (2021). Altered Position Sense after Submaximal Eccentric Exercise—inducing Central Fatigue. *Med Sci Sports Exerc*, 53(1), 218-227. <https://doi.org/10.1249/MSS.0000000000002444>
- Dieling, S., van der Esch, M., & Janssen, T. W. J. (2014). The Effect of Muscle Fatigue on Knee Joint Proprioception in Ballet Dancers and Non-dancers. *Journal of Dance Medicine & Science*, 18(4), 143-148. <https://doi.org/10.12678/1089-313X.18.4.143>
- Docherty, C. L., Moore, J. H., & Arnold, B. L. (1998). Effects of strength training on strength development and joint position sense in functionally unstable ankles. *J. Athl. Train.*, 33(4), 310-314. <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1320579/pdf/jathtrain00012-0016.pdf>
- Draz, A. H., Atya, A. M., Aboeleneen, A. M., & Elgendy, M. H. (2014). Influence of Acute Back Muscle Fatigue on Repositioning Accuracy of the Knee Joint In healthy subjects. *Journal of Medical Science and Clinical Research*, 2(1), 339-346. <https://jmscr.igmpublication.org/v2-i1/8%20jmscr.pdf>
- Drouin, J. M., Valovich-mcLeod, T. C., Shultz, S. J., Gansneder, B. M., & Perrin, D. H. (2004). Reliability and validity of the Biodex system 3 pro isokinetic dynamometer velocity, torque and position measurements. *European journal of applied physiology*, 91(1), 22-29. <https://doi.org/10.1007/s00421-003-0933-0>
- Ekstrand, J., Hägglund, M., & Waldén, M. (2011). Epidemiology of muscle injuries in professional football (soccer). *Am J Sports Med*, 39(6), 1226-1232. <https://doi.org/10.1177/0363546510395879>
- Gandevia, S. C. (2001). Spinal and supraspinal factors in human muscle fatigue. *Physiol. Rev.*, 81(4), 1725-1789. <https://doi.org/10.1152/physrev.2001.81.4.1725>
- Gandevia, S. C., & Burke, D. (1992). Does the nervous system depend on kinesthetic information to control natural limb movements? *Behavioral and*

Brain Sciences, 15, 614-632.
<https://doi.org/10.1017/S0140525X0007254X>

Gear, W. S. (2004). *The effect of increasing levels of exertion of knee joint proprioception* University of Pittsburgh]. Pittsburgh. <http://d-scholarship.pitt.edu/9536/1/gearw12022004.pdf>

Gear, W. S. (2011). Effect of different levels of localized muscle fatigue on knee position sense. *Journal of Sports Science and Medicine*, 10(4), 725-730. <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3761499/pdf/jssm-10-725.pdf>

Ghiasi, F., & Akbari, A. (2007). Comparison of the effects of open and closed kinematic chain and different target position on the knee joint position sense. *J Med Sci*, 7(6), 969-976. <https://doi.org/10.3923/jms.2007.969.976>

Givoni, N. J., Pham, T., Allen, T. J., & Proske, U. (2007). The effect of quadriceps muscle fatigue on position matching at the knee. *The Journal of physiology*, 584(1), 111-119. <https://doi.org/10.1113/jphysiol.2007.134411>

Giza, E., Mithöfer, K., Farrell, L., Zarins, B., & Gill, T. (2005). Injuries in women's professional soccer. *Br. J. Sports Med.*, 39(4), 212-216. <https://doi.org/10.1136/bjsm.2004.011973>

Gribble, P. A., & Hertel, J. (2004). Effect of lower-extremity muscle fatigue on postural control. *Arch. Phys. Med. Rehabil.*, 85(4), 589-592. <https://doi.org/10.1016/j.apmr.2003.06.031>

Haddaway, N. R., Collins, A. M., Coughlin, D., & Kirk, S. (2015). The role of Google Scholar in evidence reviews and its applicability to grey literature searching. *PloS one*, 10(9), e0138237. <https://doi.org/10.1371/journal.pone.0138237>

Hart, J. M., Kerrigan, D. C., Fritz, J. M., & Ingersoll, C. D. (2009). Jogging kinematics after lumbar paraspinal muscle fatigue. *Journal of athletic training*, 44(5), 475-481. <https://doi.org/10.4085/1062-6050-44.5.475>

- Hassanlouei, H., Arendt-Nielsen, L., Kersting, U. G., & Falla, D. (2012). Effect of exercise-induced fatigue on postural control of the knee. *Journal of electromyography and Kinesiology*, 22(3), 342-347. <https://doi.org/10.1016/j.jelekin.2012.01.014>
- Johannsen, H., Lind, T., Jakobsen, B., & Krøner, K. (1989). Exercise-induced knee joint laxity in distance runners. *Br. J. Sports Med.*, 23(3), 165-168. <https://doi.org/10.1136/bjism.23.3.165>
- Ju, Y. Y., Wang, C. W., & Cheng, H. Y. K. (2010). Effects of active fatiguing movement versus passive repetitive movement on knee proprioception. *Clinical biomechanics*, 25(7), 708-712. <https://doi.org/10.1016/j.clinbiomech.2010.04.017>
- Khan, W., Khan, M., Alradwan, H., Williams, R., Simunovic, N., & Ayeni, O. R. (2015). Utility of intra-articular hip injections for femoroacetabular impingement: a systematic review. *The Orthopaedic Journal of Sports Medicine*, 3(9), 2325967115601030. <https://doi.org/10.1177/2325967115601030>
- Kiyama, R., Kawada, M., Tokunaga, K., Ohwatashi, A., Fukudome, K., Yone, K., Yoshimoto, Y., Ohshige, T., & Maeda, T. (2014). The effect of force sensation on the ability to control muscle force during fatigue condition. *Isokinetics and exercise science*, 22(4), 287-293. <https://doi.org/10.3233/ies-140550>
- Lattanzio, P. J., Petrella, R. J., Sproule, J. R., & Fowler, P. J. (1997). Effects of fatigue on knee proprioception. *Clinical Journal of Sport Medicine*, 7(1), 22-27. <https://doi.org/10.1097/00042752-199701000-00005>
- Lee, T., & Chow, D. (2013). Effects of whole body vibration on spinal proprioception in normal individuals. 35th Annual International Conference of the IEEE EMBS, Osaka, Japan.
- Lephart, S. M., Pincivero, D. M., Giraido, J. L., & Fu, F. H. (1997). The role of proprioception in the management and rehabilitation of athletic injuries.

The American journal of sports medicine, 25(1), 130-137.
<https://doi.org/10.1177/036354659702500126>

Lephart, S. M., Pincivero, D. M., & Rozzi, S. L. (1998). Proprioception of the ankle and knee. *Sports medicine*, 25(3), 149-155. [https://doi.org/0112-1642/98/0003-0149/\\$03.50/0](https://doi.org/0112-1642/98/0003-0149/$03.50/0)

Lephart, S. M., Riemann, B. L., & Fu, F. H. (2000). Introduction to the sensorimotor system. In S. M. Lephart & F. H. Fu (Eds.), *Proprioception and Neuromuscular Control in Joint Stability* (pp. 37–51). IL: Human Kinetics.

Marks, R. (1994). Effect of exercise-induced fatigue on position sense of the knee. *Australian Journal of Physiotherapy*, 40(3), 175-181.
[https://doi.org/10.1016/S0004-9514\(14\)60576-6](https://doi.org/10.1016/S0004-9514(14)60576-6)

Marks, R., & Quinney, H. A. (1993). Effect of fatiguing maximal isokinetic quadriceps contractions on ability to estimate knee-position. *Perceptual and motor skills*, 77((3_suppl)), 1195-1202.
<https://doi.org/10.2466/pms.1993.77.3f.1195>

Miura, K., Ishibashi, Y., Tsuda, E., Okamura, Y., Otsuka, H., & Toh, S. (2004). The effect of local and general fatigue on knee proprioception. *Arthroscopy: The Journal of Arthroscopic and Related Surgery*, 20(4), 414-418. <https://doi.org/10.1016/j.arthro.2004.01.007>

Mohammadi, F., Azma, K., Naseh, I., Emadifard, R., & Etemadi, Y. (2013). Military Exercises, Knee and Ankle Joint Position Sense, and Injury in Male Conscripts: A Pilot Study. *Journal of athletic training*, 48(6), 790-796.
<https://doi.org/10.4085/1062-6050-48.3.06>

Niederseer, D., Mörtl, H., Liebensteiner, M. C., Egger, A., Thaler, C. W., Plöderl, M., Niebauer, J., & Raschner, C. (2014). General fatigue and joint position sense in male elite handball players. *Deutsche Zeitschrift für Sportmedizin*, 65(6), 149-153. <https://doi.org/10.5960/dzsm.2014.129>

- Nitsure, P., & Prabhu, S. (2015). Study of Differences in Proprioception of Knee Joint with Age, Gender and Lower Limb Dominance in Healthy Asymptomatic Individuals: An Observational Study. *Sports medicine*, 2015(2), 1-5.
- Olsson, L., Lund, H., Henriksen, M., Rogind, H., Bliddal, H., & Danneskiold-Samsøe, B. (2004). Test–retest reliability of a knee joint position sense measurement method in sitting and prone position. *Adv. Physiother.*, 6(1), 37-47. <https://doi.org/10.1080/14038190310009894>
- Page, M. J., Moher, D., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., & Brennan, S. E. (2021). PRISMA 2020 explanation and elaboration: updated guidance and exemplars for reporting systematic reviews. *bmj*, 372(160), 1-36. <https://doi.org/10.1136/bmj.n160>
- Paschalis, V., Nikolaidis, M. G., Giakas, G., Jamurtas, A. Z., Pappas, A., & Koutedakis, Y. (2007). The effect of eccentric exercise on position sense and joint reaction angle of the lower limbs. *Muscle & nerve*, 35(4), 496-503. <https://doi.org/10.1002/mus.20723>
- Paschalis, V., Nikolaidis, M. G., Theodorou, A. A., Deli, C. K., Raso, V., Jamurtas, A. Z., Giakas, G., & Koutedakis, Y. (2013). The effects of eccentric exercise on muscle function and proprioception of individuals being overweight and underweight. *J Strength Cond Res*, 27(9), 2542-2551. <https://doi.org/10.1519/JSC.0b013e31827fc9a6>
- Paschalis, V., Nikolaidis, M. G., Theodorou, A. A., Giakas, G., Jamurtas, A. Z., & Koutedakis, Y. (2010). Eccentric exercise affects the upper limbs more than the lower limbs in position sense and reaction angle. *Journal of sports sciences*, 28(1), 33-43. <https://doi.org/10.1080/02640410903334764>
- Pedersen, J., Ljubisavljevic, M., Bergenheim, M., & Johansson, H. (1998). Alterations in information transmission in ensembles of primary muscle spindle afferents after muscle fatigue in heteronymous muscle. *Neurosci.*, 84(3), 953-959. [https://doi.org/10.1016/S0306-4522\(97\)00403-X](https://doi.org/10.1016/S0306-4522(97)00403-X)

- Pedrinelli, A., da Cunha Filho, G. A. R., Thiele, E. S., & Kullak, O. P. (2013). Estudo epidemiológico das lesões no futebol profissional durante a Copa América de 2011, Argentina. *Rev Bras Ortop.*, 48(2), 131-136. <https://doi.org/10.1016/j.rbo.2012.09.001>
- Proske, U. (2019). Exercise, fatigue and proprioception: a retrospective. *Exp Brain Res*, 237(10), 2447-2459. <https://doi.org/10.1007/s00221-019-05634-8>
- Proske, U. (2023). A reassessment of the role of joint receptors in human position sense. *Exp. Brain Res.*, 241(4), 943-949. <https://doi.org/10.1007/s00221-023-06582-0>
- Proske, U., & Gandevia, S. C. (2012). The proprioceptive senses: their roles in signaling body shape, body position and movement, and muscle force. *Physiol Rev.*, 92(4), 1651-1697. <https://doi.org/10.1152/physrev.00048.2011>
- Proske, U., Wise, A., & Gregory, J. (2000). The role of muscle receptors in the detection of movements. *Prog. Neurobiol.*, 60(1), 85-96. [https://doi.org/10.1016/S0301-0082\(99\)00022-2](https://doi.org/10.1016/S0301-0082(99)00022-2)
- Ribeiro, F., Mota, J., & Oliveira, J. (2007). Effect of exercise-induced fatigue on position sense of the knee in the elderly. *European journal of applied physiology*, 99(4), 379-385. <https://doi.org/10.1007/s00421-006-0357-8>
- Ribeiro, F., Santos, F., Gonçalves, P., & Oliveira, J. (2008). Effects of volleyball match-induced fatigue on knee joint position sense. *European Journal of Sport Science*, 8(6), 397-402. <https://doi.org/10.1080/02614360802373060>
- Ribeiro, F., Venâncio, J., Quintas, P., & Oliveira, J. (2011). The effect of fatigue on knee position sense is not dependent upon the muscle group fatigued. *Muscle and Nerve*, 44(2), 217-220. <https://doi.org/10.1002/mus.22018>
- Riemann, B. L., & Lephart, S. M. (2002). The sensorimotor system, part I: the physiologic basis of functional joint stability. *Journal of athletic training*,

- 37(1), 71-79.
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC164311/pdf/attr_37_01_0071.pdf
- Riemann, B. L., Myers, J. B., & Lephart, S. M. (2002). Sensorimotor system measurement techniques. *J. Athl. Train.*, 37(1), 85-98.
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC164313/pdf/attr_37_01_0085.pdf
- Roberts, D., Ageberg, E., Andersson, G., & Fridén, T. (2003). Effects of short-term cycling on knee joint proprioception in healthy young persons. *American Journal of Sports Medicine*, 31(6), 990-994.
<https://doi.org/10.1177/03635465030310064001>
- Romero-Franco, N., & Jiménez-Reyes, P. (2017). Effects of Warm-Up and Fatigue on Knee Joint Position Sense and Jump Performance. *Journal of motor behavior*, 49(2), 117-122.
<https://doi.org/10.1080/00222895.2016.1152222>
- Rozzi, S., Yuktanandana, P., Pincivero, D., & Lephart, S. (2000). Role of fatigue on proprioception and neuromuscular control. In *Proprioception and neuromuscular control in joint stability*. (pp. 375-384). IL: Human Kinetics.
- Salgado, E., Ribeiro, F., & Oliveira, J. (2015). Joint-position sense is altered by football pre-participation warm-up exercise and match induced fatigue. *Knee*, 22(3), 243-248. <https://doi.org/10.1016/j.knee.2014.10.002>
- Sayyadi, P., Minoonejad, H., Seidi, F., Shikhhoseini, R., & Arghadeh, R. (2024). The effectiveness of fatigue on repositioning sense of lower extremities: systematic review and meta-analysis. *BMC Sports Sci Med Rehabil*, 16(1), 35. <https://doi.org/10.1186/s13102-024-00820-w>
- Sherrington, C. S. (1920). *The Integrative Action of the Nervous System* (6^a ed.). Yale University Press.
- Shokri, P., Eslamian, F., Shakouri, S. K., Ohanian, S., & Jahanjoo, F. (2018). Fatigue Induced Effects after Concentric versus Eccentric Exercises on

- Sense of Force and Senses of Position among Young Normal Adults-A Controlled Single-Blinded Study. *J. res. med. dent. sci.*, 6(3), 258-267. <https://doi.org/10.24896/jrmds.20186340>
- Skinner, H. B., Wyatt, M. P., Hodgdon, J. A., Conard, D. W., & Barrack, R. L. (1986). Effect of fatigue on joint position sense of the knee. *Journal of Orthopaedic Research*, 4(1), 112-118. <https://doi.org/10.1002/jor.1100040115>
- Slim, K., Nini, E., Forestier, D., Kwiatkowski, F., Panis, Y., & Chipponi, J. (2003). Methodological index for non-randomized studies (MINORS): development and validation of a new instrument. *ANZ journal of surgery*, 73(9), 712-716. <https://doi.org/10.1046/j.1445-2197.2003.02748.x>
- Sonkodi, B., Hegedűs, Á., Kopper, B., & Berkes, I. (2022). Significantly Delayed Medium-Latency Response of the Stretch Reflex in Delayed-Onset Muscle Soreness of the Quadriceps Femoris Muscles Is Indicative of Sensory Neuronal Microdamage. *Journal of Functional Morphology and Kinesiology*, 7(2), 43. <https://doi.org/10.3390/jfmk7020043>
- Steiner, M., Grana, W., Chillag, K., & Schelberg-Karnes, E. (1986). The effect of exercise on anterior-posterior knee laxity. *Am J Sports Med*, 14(1), 24-29. <https://doi.org/10.1177/036354658601400105>
- Sterne, J. A. C., Savović, J., Page, M. J., Elbers, R. G., Blencowe, N. S., Boutron, I., Cates, C. J., Cheng, H.-Y., Corbett, M. S., Eldridge, S. M., Emberson, J. R., Hernán, M. A., Hopewell, S., Hróbjartsson, A., Junqueira, D. R., Jüni, P., Kirkham, J. J., Lasserson, T., Li, T., McAleenan, A., Reeves, B. C., Shepperd, S., Shrier, I., Stewart, L. A., Tilling, K., White, I. R., Whiting, P. F., & Higgins, J. P. T. (2019). RoB 2: a revised tool for assessing risk of bias in randomised trials. *bmj*, 366, l4898. <https://doi.org/10.1136/bmj.l4898>
- Torres, R., Vasques, J., Duarte, J. A., & Cabri, J. M. H. (2010). Knee proprioception after exercise-induced muscle damage. *International*

journal of sports medicine, 31(6), 410-415. <https://doi.org/10.1055/s-0030-1248285>

Vila-Chã, C., Riis, S., Lund, D., Møller, A., Farina, D., & Falla, D. (2011). Effect of unaccustomed eccentric exercise on proprioception of the knee in weight and non-weight bearing tasks. *Journal of electromyography and Kinesiology*, 21(1), 141-147. <https://doi.org/10.1016/j.jelekin.2010.10.001>

Voight, M. L., Hardin, J. A., Blackburn, T. A., Tippet, S., & Canner, G. C. (1996). The effects of muscle fatigue on and the relationship of arm dominance to shoulder proprioception. *J. Orthop. Sports Phys. Ther.*, 23(6), 348-352. <https://doi.org/10.2519/jospt.1996.23.6.348>

Chapter 3

Normative values and accuracy-influencing factors for knee joint-position sense assessments: a cross-sectional study

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Abstract

Background: Normative values for knee joint-position sense (KJPS) allow the identification of individuals with reduced proprioception and compromised joint stability. This study aimed to provide normative values in different KJPS assessments for healthy young individuals. The secondary aim was to investigate which protocol-related factors produce higher accuracy, as well as the influence of individual factors on the KJPS.

Methods: A cross-sectional study was conducted with 62 participants. KJPS of both limbs was assessed actively to two target angles (20°/45°) in three test positions, and expressed in absolute angular errors (AAE). In the sitting and prone positions, concentric and eccentric repositionings were performed, while the standing tests involved unilateral and bilateral squats.

Results: Considering the 20°/45° angles, normative values for the sitting tests were 3.0°/3.7° for the concentric repositioning, and 2.7°/3.6° for the eccentric repositioning. For the prone tests, the values were 4.0°/4.8° for the concentric repositioning, and 4.8°/4.9° for the eccentric repositioning. In standing tests, the values were 2.8°/2.5° in unipedal, and 4.3°/3.0° in bipedal. Significantly higher AAE were found in the prone position tests, compared to sitting and standing ($p < 0.001$), while no differences were found between sitting and standing positions ($p = 0.167$). The bipedal test produced significantly higher AAE than the unipedal ($p = 0.001$). At 45°, AAE were generally higher in sitting and prone tests, but lower in standing tests ($p < 0.05$). AAE did not differ between: concentric/eccentric repositionings, dominant/non-dominant limbs, and male/female ($p > 0.05$).

Conclusion: This study provides normative data covering different KJPS assessments for healthy young individuals. Regarding protocol-related factors: prone position led to worse accuracy; the type of repositioning does not impact accuracy; extreme angles produced better accuracy in sitting/prone tests, but worse in standing tests. Individual factors (sex or dominance) do not influence the KJPS.

Keywords: normative values; knee; joint-position sense; proprioception; healthy

Introduction

Joint-position sense (JPS) assesses the accuracy to reproduce a formerly demonstrated joint angle, without relying on visual information (Riemann et al., 2002). A recent systematic review observed several protocols to assess the knee JPS, pointing out different parameters that should be considered, and whose influence should be further explored (Azevedo, Moreira-Silva, et al., 2024), such as: (i) the method of positioning and repositioning (active and/or passive) (Ju et al., 2010); (ii) the test position (sitting, lying down or standing), that will determine if the test will be conducted in weight-bearing or non-weight-bearing conditions (Lokhande et al., 2013; Olsson et al., 2004); (iii) the motion direction (to flexion and/or to extension), which will define the type of repositioning (concentric or eccentric) (Clark et al., 2016); (iv) the assessed limbs (dominant, non-dominant or both) (Azevedo, Rodrigues, et al., 2024); and (v) the target angles (intermediate and/or extreme angles of the knee joint range of motion) (Gear, 2011).

Different mechanoreceptors ensure a continuous input to the Central Nervous System (CNS), allowing the recognition of the knee position in space. According to Proske (2023), muscle spindles are muscle mechanoreceptors capable of providing positional information across a full joint range of motion (ROM), despite being particularly active in intermediate ranges (Docherty et al., 1998), and especially between 40°-80° of knee flexion (Olsson et al., 2004). Joint mechanoreceptors can be targeted when JPS is assessed at extreme angles (Proske, 2023; Riemann & Lephart, 2002). This highlights that the choice of the target angles must be carefully considered according to the mechanoreceptors whose integrity is intended to be assessed. In this line of reasoning, there is also the choice of conducting active and/or passive positionings and repositionings. Passive tests are mainly used to target joint mechanoreceptors, while active tests mostly target the muscle ones, despite not being possible to completely isolate the contribution of each of the mechanoreceptors in the active or passive tests (Barrett et al., 1991; Lephart et al., 1997). Finally, regarding motion direction, the available published studies focus on protocols involving concentric repositionings

(Azevedo, Moreira-Silva, et al., 2024), disregarding the eccentric motions, which have been described to cause greater stimuli on the muscle spindles (LaStayo et al., 2003), not being known the impact of an eccentric repositioning compared to a concentric one on the knee JPS accuracy.

The selection of the test position determines whether the assessment is performed in weight-bearing (closed kinetic chain) or non-weight-bearing conditions (open kinetic chain). While it is argued that weight-bearing assessments better mimic the functional activities of the lower limbs (Andersen et al., 1995), these tests do not allow an isolated assessment of a joint. Thus, non-weight-bearing assessments should not be disregarded when an assessment of the proprioceptive acuity of a specific joint is intended (Stillman & McMeeken, 2001).

Regarding individual factors, and specifically the influence of dominance, the preference for using the dominant limb for more dynamic gestures, and the non-dominant limb for stability or support actions (Fousekis et al., 2010; Teixeira et al., 2011), in theory, could produce differences between limbs. However, dominance still has not reached a consensus regarding its influence on the knee JPS. On one hand, individuals who practice sports show no differences between the dominant and non-dominant limbs (Azevedo et al., 2021; Muaidi et al., 2009). Conversely, in non-trained individuals, the dominant limb seems to present higher accuracy than the non-dominant (Azevedo et al., 2021). In that sense, further studies assessing both limbs are still required to help reach a deeper understanding of the involved mechanisms.

Concerning the influence of sex, Fouladi et al. (2012) revealed that females present different levels of knee JPS during one menstrual cycle. However, small sample studies seem to suggest no differences in the proprioceptive accuracy between male and female individuals (Busch et al., 2023), which needs further investigation.

Establishing normative values regarding knee JPS assessments allows the identification of individuals with reduced proprioception and probable compromised joint stability. Consequently, an increased risk of knee injury may

emerge both during daily activities and sports practice. In the sports context, normative values may also be required to monitor the effectiveness of rehabilitation programs (Relph & Herrington, 2016), or to assist in the return-to-sport decision when values are comparable to those before injury (Haggerty et al., 2021). Previous studies have provided normative data regarding knee JPS assessments (Lau et al., 2024; Lee & Lim, 2023; Relph & Herrington, 2016). However, in the studies of Relph and Herrington (2016) and Lau et al. (2024), only normative values for sitting tests (in non-weight bearing conditions) were defined, and in the case of Lee and Lim (2023), for a sitting and an unipedal test. In both studies, the few assessed tests do not reflect all functional activities in which individuals might be engaged during daily living or sports practice. Thus, normative data in other knee JPS assessments, as well as the knowledge about which tests produce higher accuracy when repositioning, remain scarce.

In that sense, the primary aim of this study was to provide normative values in different knee JPS assessments for healthy young individuals. As a secondary aim, this study investigated which protocol-related factors produce higher accuracy (test position, type of repositioning, and target angle), as well as the influence of individual factors (sex and dominance) on the knee JPS. For that purpose, different test positions were assessed (in sitting, prone, and standing), as well as different types of repositionings (concentric and eccentric) and target angles (extreme and intermediate) were applied.

Methods

Study Design and Participants

This cross-sectional study is reported following the Strengthening the Reporting of Observational studies in Epidemiology (STROBE) recommendations (Vandenbroucke et al., 2007). The study was approved by the Ethics Committee

of Fernando Pessoa University, with the code ESS/PI-621/24-2, on 21st October 2024. All participants signed an informed consent form to participate in the study, and all procedures were conducted according to the Helsinki Declaration. Data collections took place at the facilities of a physical therapy teaching clinic, between November and December 2024.

The study consisted of a convenience sample of 62 healthy young participants (37 males and 25 females). Volunteers of both sexes were included if they were aged between 18 and 30 years old; had normal knee flexion and extension ROM; and negative knee joint integrity tests (anterior drawer, Lachman's test, posterior drawer, valgus and varus stress tests), which were assessed by an experienced physical therapist. Excluded were those who self-reported: history of lower limbs injuries in the last six months, or history of lower limbs surgery; a neurological disease or vestibular pathology; and those who were using medications that could affect the central nervous system, balance, or motor control. Additionally, participants were asked to avoid alcohol and fatiguing exercise in the 48 hours before the day of assessment.

The eligible participants answered a sample characterization questionnaire, assessing variables such as: age, sex, weight, height, and lower limb dominance, which was defined as the preferred lower limb to kick a ball. Body mass index (BMI) was later calculated by the investigators. The International Physical Activity Questionnaire (IPAQ) Short-Form was also filled out to establish their physical activity level, and, according to the instructions of the IPAQ Research Committee (2005), participants were further categorized as having a low, moderate, or high physical activity level.

Knee Joint-Position Sense Assessments

Knee JPS assessments were conducted with the participants blindfolded, barefoot, and in a silent environment. For all assessments, both limbs were assessed describing an ipsilateral repositioning and considering two target angles of 20° and 45° of knee flexion (Azevedo, Rodrigues, et al., 2024). These

positions were demonstrated using the digital goniometer Parkside® HG00962B (Kompernass Handels GMBH, Bochum, Germany).

The knee JPS assessments were performed in three test positions: sitting, prone, and standing. For sitting and prone positions (non-weight bearing tests in open-kinetic chain), two tests were performed, involving two knee motion directions, describing two types of repositioning (concentric and eccentric) (Clark et al., 2016).

In the sitting position (Figure 1), the concentric repositioning test started from the initial position of 90° of knee flexion, and participants had to reposition the leg into extension to one of the target angles; while in the eccentric repositioning test, the knee started at full extension, with the participants having to perform a flexion towards one of the target angles.

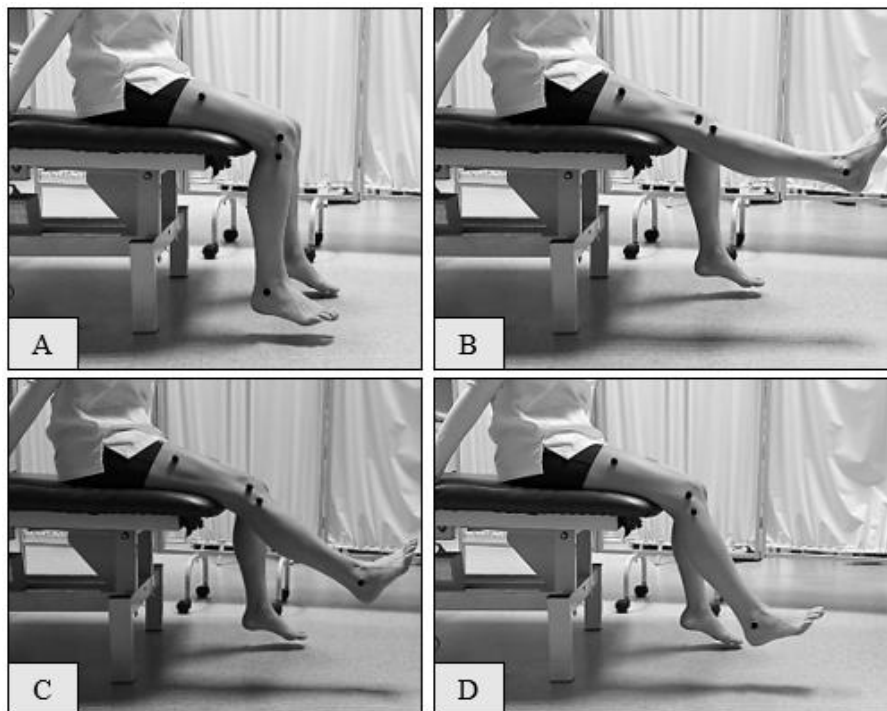


Figure 1: Illustration of the knee JPS tests in the sitting position: (A) initial position for the concentric repositioning test (to extension); and (B) initial position for the eccentric repositioning test (to flexion); (C) describes the leg positioned at the target angle of 20° and (D) at 45° of knee flexion.

Regarding prone assessments (Figure 2), the concentric repositioning test started with the knee fully extended, having then to describe a knee flexion to reach the target angles; and in the eccentric repositioning test, the knee started flexed at 90°, from which a knee extension had to be performed until the target angles were reached.

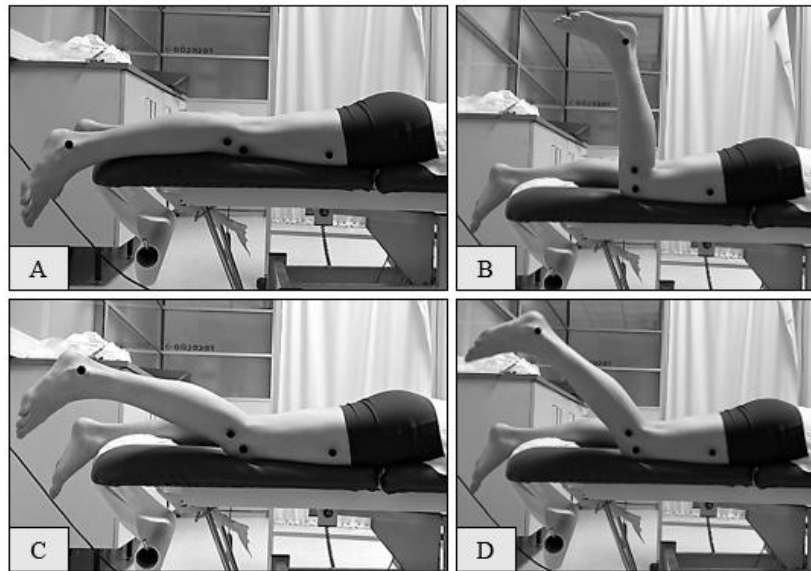


Figure 2: Illustration of the knee JPS tests in the prone position: (A) initial position for the concentric repositioning test (to flexion); (B) initial position for the eccentric repositioning test (to extension); (C) describes the leg positioned at the target angle of 20° and (D) at 45° of knee flexion.

Finally, for the standing tests (Figures 3 and 4), participants performed both a unilateral (Lokhande et al., 2013) and a bilateral squat (Ghiasi & Akbari, 2007) (weight-bearing tests in closed-kinetic chain). In both tests, participants started in full knee extension, and had to squat until the target angle, describing an eccentric repositioning. In the unipedal test, support on a chair in front was allowed to maintain balance.

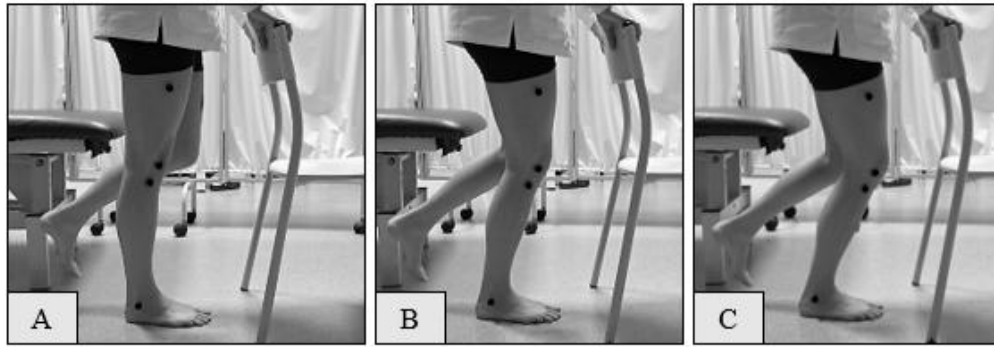


Figure 3: Illustration of the knee JPS assessments in the standing position, demonstrating the unilateral squat: (A) initial position; (B) describes the leg positioned at the target angle of 20°; and (C) at 45° of knee flexion.

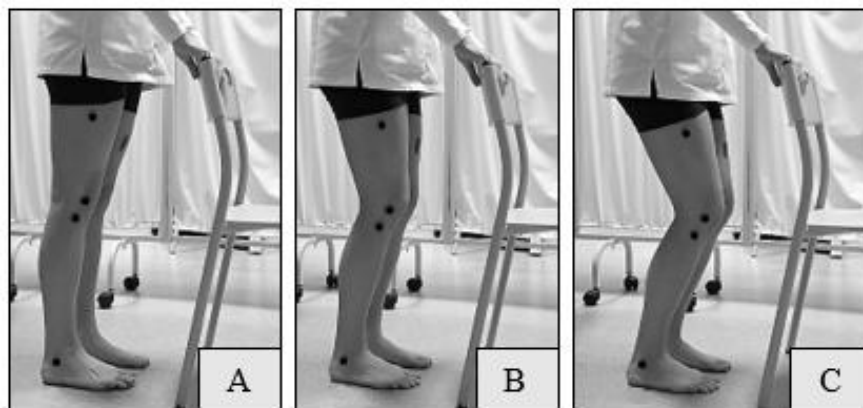


Figure 4: Illustration of the knee JPS assessments in the standing position, demonstrating the bilateral squat: (A) initial position; (B) describes the leg positioned at the target angle of 20°; and (C) at 45° of knee flexion.

The order of the lower limbs (dominant/non-dominant), test positions (sitting, prone, standing), types of repositioning (concentric/eccentric), and target angles (20°/45°) was randomized.

In the sitting and prone assessments, from the initial positions, the investigator slowly moved the participant's leg towards one of the target angles (passive positioning), asking them to hold and memorize the position for five seconds. Afterwards, they had to return to the initial position and immediately try to achieve the previously demonstrated angle as precisely as possible, describing an active repositioning. For the standing tests, the participants actively and slowly squatted until the investigator verbalized to stop, as the position was reached. For all

assessments, three attempts to reposition were given, and the average of the three was considered (Salgado et al., 2015).

These procedures were recorded using the smartphone Samsung Galaxy A25 5G video camera (Samsung Electronics Co., Ltd., Suwon, South Korea) mounted on a tripod, at a distance ensuring that all markers were within the field of view. Four black markers were fixed to the skin with double-sided adhesive tape in: (i) the head of the fibula; (ii) lateral malleolus; (iii) half distance between the greater trochanter and the lateral epicondyle of the femur; and (iv) the lateral epicondyle of the femur (Clark et al., 2016). The videos were then processed in the Kinovea 0.8.15 software. Three frames from the last three seconds of each positioning and repositioning were analysed. Repositioning errors were reported as the absolute angular errors (AAE), calculated as the absolute value of the difference between the target angle and the achieved angle by the participant (Bennell et al., 2005).

Statistical analysis

Data analysis was conducted in the statistical software IBM SPSS version 26 for Windows (IBM Corp., Armonk, NY, USA), considering a significance level of 5%. The Kolmogorov-Smirnov test was applied to assess normality in the data distribution, which was not confirmed. In that sense, the descriptive analysis of the continuous variables (age, body mass, height, BMI, and AAE) was carried out using Median and Interquartile Range (Mdn; IQR). Nominal variables (sex and dominance) were described as frequency (n) and percentage (%).

Non-parametric tests were chosen to check for differences in the AAE regarding protocol-related and individual factors. The Mann-Whitney test was used for the comparison of the AAE between males and females. The Friedman test was conducted to assess differences between the three test positions (sitting, prone, and standing). Finally, the Wilcoxon test was used to compare the AAE between: (i) dominant and non-dominant limb, (ii) concentric and eccentric repositionings; (iii) unipedal and bipedal tests; and (iv) target angles (20° and 45°). Additionally,

effect size (r) was calculated by dividing the Z statistic by the square root of the number of observations ($r = Z/\sqrt{N}$) (Rosenthal, 1991). Cohen (1988) has suggested 0.10, 0.30, and 0.50, respectively, as indicative of small, medium, and large effects.

Results

Sixty-two participants, 37 males (59.7%) and 25 females (40.3%), participated in the study. Table 1 describes the sample characterization in terms of age, body mass, height, and BMI of the total sample and by sex group.

The dominant limb was the right in 54 participants (87.1%) and the left in 8 participants (12.9%). Regarding the physical activity level, 12 participants (19.4%) were classified as having a low level, 20 (32.3%) a moderate level, and 30 (48.4%) a high level of physical activity.

Table 1. Characterization of the total sample and by sex group, regarding age, body mass, height, and BMI.

	Total (n = 62)	Males (n = 37)	Females (n = 25)
Age (years)	22 (3)	23 (3)	22 (2)
Body mass (kg)	72.5 (19.3)	76.8 (14.0)	60.0 (17.5)
Height (m)	1.75 (0.12)	1.80 (0.08)	1.65 (0.07)
BMI (kg/m ²)	22.72 (5.67)	24.07 (4.92)	21.15 (6.06)

Note: Variables are described as Median (Interquartile Range).

Normative values and influence of individual factors (sex and dominance)

Normative knee JPS values for the different assessed tests are detailed in Table 2, considering the AAE of the total sample and according to male and female participants.

Table 2 also displays the comparisons of AAE between males and females, and between dominant and non-dominant limbs of the different applied JPS tests. The results revealed that there were neither differences related to sex nor between dominant and non-dominant limbs ($p > 0.05$). In that sense, the normative values were reported without sex or dominance discrimination, considering the average values calculated between the median of AAE of the dominant and non-dominant limbs.

For the sitting position tests, the values for the 20°/45° angles were: 3.0°/3.7° for the concentric repositioning test, and 2.7°/3.6° for the eccentric repositioning test.

For the prone tests, the values for the 20°/45° angles were: 4.0°/4.8° for the concentric repositioning test, and 4.8°/4.9° for the eccentric repositioning test.

Regarding standing position tests, the values for the 20°/45° angles were: 2.8°/2.5° for the unipedal test, and 4.3°/3.0° for the bipedal test.

Table 2. Normative values (AAE) and sex (male vs. female) and dominance (dominant vs. non-dominant limb) comparisons across the different knee JPS tests (in degrees).

Test position	Type of reposition	Target angle	Limb	Total	Male	Female	p^a
SIT	Concentric	20°	DOM	2.9 (3.3)	2.7 (3.5)	3.2 (3.7)	0.354
			NDOM	3.0 (2.5)	3.2 (1.9)	2.7 (3.6)	0.434
			p^b	0.831			
		45°	DOM	3.5 (4.4)	3.3 (5.1)	3.8 (3.2)	0.556
			NDOM	3.8 (3.6)	4.3 (3.3)	2.7 (4.2)	0.187
			p^b	0.520			
	Eccentric	20°	DOM	2.2 (2.6)	2.3 (2.3)	2.1 (2.8)	0.600
			NDOM	3.2 (3.6)	3.2 (3.4)	2.7 (3.8)	0.736
			p^b	0.064			
		45°	DOM	3.6 (4.7)	3.3 (3.7)	5.1 (6.0)	0.069
			NDOM	3.6 (5.2)	3.6 (5.0)	4.0 (5.9)	0.994
			p^b	0.917			

Table 2 (Cont.). Normative values (AAE) and sex (male vs. female) and dominance (dominant vs. non-dominant limb) comparisons across the different knee JPS tests (in degrees).

Test position	Type of reposition	Target angle	Limb	Total	Male	Female	p^a
PRONE	Concentric	20°	DOM	4.0 (6.1)	5.0 (6.5)	3.7 (4.8)	0.447
			NDOM	4.0 (6.1)	3.6 (4.9)	4.1 (8.6)	0.774
			p^b	0.934			
		45°	DOM	4.8 (6.1)	5.5 (6.0)	2.8 (6.6)	0.397
			NDOM	4.8 (6.2)	4.8 (6.2)	4.8 (5.4)	0.920
			p^b	0.268			
	Eccentric	20°	DOM	4.5 (5.3)	3.7 (4.8)	5.1 (6.4)	0.863
			NDOM	5.1 (7.5)	4.7 (4.5)	7.3 (9.1)	0.081
			p^b	0.546			
		45°	DOM	4.5 (5.3)	4.6 (5.5)	4.3 (4.6)	0.626
			NDOM	5.3 (4.4)	5.1 (3.8)	6.0 (5.0)	0.381
			p^b	0.428			
STANDING	Unipedal	20°	DOM	2.6 (4.1)	2.3 (3.9)	3.7 (4.4)	0.166
			NDOM	3.0 (2.8)	3.0 (3.3)	3.0 (3.0)	0.575
			p^b	0.242			
		45°	DOM	2.5 (3.1)	2.8 (3.3)	2.3 (2.3)	0.214
			NDOM	2.4 (3.2)	2.4 (2.5)	2.2 (3.6)	0.464
			p^b	0.604			
	Bipedal	20°		4.3 (4.6)	4.7 (4.8)	2.9 (4.1)	0.157
		45°		3.0 (3.6)	3.5 (3.8)	2.9 (3.1)	0.625

Note: Variables are described as Median (Interquartile Range); DOM: dominant limb; NDOM: non-dominant limb; p^a : Mann-Whitney test for sex comparisons; p^b : Wilcoxon test for between-limbs comparisons

Influence of protocol-related factors (test position, type of repositioning, and target angles)

Since no significant differences between limbs were verified, the following analyses were conducted by pooling the AAE values of the two limbs.

Regarding the test positions (sitting vs. prone vs. standing), in ascending order of the median value of the AAE, the standing position registered a 2.9° (3.5),

followed by the sitting position with 3.1° (3.8), and finally, the prone position with 4.8° (5.6). The Friedman test revealed a significant difference in the AAE between the test positions ($p < 0.001$). Pairwise comparisons showed significant differences between the prone position and both the sitting ($p < 0.001$, $r = 0.29$) and standing positions ($p < 0.001$, $r = 0.36$), with the prone position registering significantly higher AAE than the other two test positions. No differences were found in the AAE between the sitting and standing test positions ($p = 0.167$, $r = 0.06$).

Regarding the type of repositioning (concentric vs. eccentric), the median value of the AAE in the sitting position, for the concentric and eccentric repositioning, was 3.2° (3.6) and 3.0° (4.0), respectively. In the prone position, the median value of the AAE was 4.6° (6.1) and 4.9° (5.3) for the concentric and eccentric repositionings, respectively. No differences between types of repositionings were found, neither in the sitting position ($p = 0.904$, $r = 0.02$) nor in the prone position ($p = 0.271$, $r = 0.22$).

Regarding standing tests, the median value of AAE for the unipedal tests was 2.6° (3.4), and for the bipedal tests was 3.4° (3.6). A significant difference was confirmed between these tests ($p = 0.001$, $r = 0.70$), with the AAE of the bipedal test being significantly higher than the unipedal test.

The comparison of AAE between the two tested target angles (20° and 45°) is described in Table 3. The AAE in the sitting and prone test positions seem to be higher for the assessments to the 45° target angle, although a significant difference was only found in the eccentric repositioning of the sitting test ($p < 0.001$, $r = 0.75$). On the contrary, the AAE were significantly higher in the 20° target angle in both the unipedal ($p = 0.035$, $r = 0.43$) and bipedal tests ($p < 0.001$, $r = 0.73$).

Table 3. Comparison of AAE between target angles (20° vs. 45°) across the different JPS tests (in degrees).

Test position	Type of reposition	Target angle	AAE	p^a
SIT	Concentric	20°	3.0 (2.8)	0.074
		45°	3.6 (3.9)	
	Eccentric	20°	2.7 (3.0)	<0.001*
		45°	3.6 (4.9)	
PRONE	Concentric	20°	4.0 (6.3)	0.857
		45°	4.8 (5.3)	
	Eccentric	20°	4.9 (7.1)	0.267
		45°	4.9 (5.1)	
STANDING	Unipedal	20°	3.0 (3.4)	0.035*
		45°	2.4 (3.1)	
	Bipedal	20°	4.3 (4.4)	<0.001*
		45°	3.0 (3.4)	

Note: Variables are described as Median (Interquartile Range); AAE: absolute angular errors; p^a : Wilcoxon test; * $p < 0.05$

Discussion

The primary aim of this study was to provide normative values in different knee JPS assessments for healthy young individuals. As a secondary aim, this study investigated which protocol-related factors produce fewer errors (test position, type of repositioning, and target angle), as well as the influence of individual factors (sex and dominance) on the knee JPS.

This study used a video camera to record the knee motions during JPS assessments, which has been described as the second most-used instrument after the isokinetic dynamometer (Azevedo, Moreira-Silva, et al., 2024). The validity of image capture compared with the isokinetic dynamometer was previously reported, with the conclusions supporting that this is a valid method to assess the knee JPS (Relph & Herrington, 2015). The videos were later analysed

with the Kinovea software, which was likewise considered reliable to assess knee joint motions (Itokazu, 2022).

Normative values for knee JPS assessments

Previous studies have provided normative data for knee JPS assessments (Lau et al., 2024; Lee & Lim, 2023; Relph & Herrington, 2016). However, few tests were performed, with the reported results being limited to sitting and unipedal tests. In addition, only one study reports values for concentric and eccentric repositionings (Relph & Herrington, 2016), and only one study distinguishes normative values between extreme and intermediate angles (Lee & Lim, 2023). For these reasons, the present study covers these gaps by providing normative values for more test positions, types of repositioning, and target angles.

For the sitting position tests, the present results reported normative values for the 20°/45° target angles of 3.0°/3.7° for the concentric repositioning test, and 2.7°/3.6° for the eccentric repositioning test, respectively. In this test position, the normative values reported by Relph and Herrington (2016) for the concentric and eccentric repositionings were 2.7° and 3.6°, respectively, considering only intermediate angles. Comparing these results to the values of the present study for the 45° angle, regarding the concentric repositioning, the values differ by 1° (3.7° vs. 2.7°), and are similar for the eccentric repositioning (3.6° vs. 3.6°). Lee and Lim (2023), although assessing their participants only by a concentric repositioning, reported a normative value of 2.03° and 3.05° for the target angles of 30° and 50°, respectively. Comparing the results of the concentric repositioning obtained in the extreme angle of 20° of the present study with the 30° (3.0° vs. 2.03°), and comparing the intermediate angles of 45° with the 70° (3.7° vs. 3.05°), a difference lower than 1° is seen for both angles. Despite the observed difference in the reported errors is still small, it is essential to mention that this may be attributed to the fact that these studies confirmed a normal variable distribution and described the variables using different central tendency measures (mean value), unlike the present study where the median value was reported, as a normal distribution was not observed. Moreover, the sample sizes of the

compared studies are smaller than those of the present research considering the same age group. Effectively, Relph and Herrington (2016) reported normative values for young individuals (15 - 29 years) based on 29 participants, and the results of Lee and Lim (2023) are based on 21 participants within the 20 - 29 age group. The results of the present study are based on the assessments of 62 participants. Likewise, as distinct target angles were used, it is possible that in the two extreme angles (20° and 30°), different local compression in the joint mechanoreceptors may occur. Similarly, the intermediate angles (45° and 70°) are quite distant, so if the range of repositioning is not the same, the muscle stretch to which the muscle spindle is sensitive may also be distinct, impacting differently the accuracy.

Lee and Lim (2023) also provided a normative value considering an unipedal test of 1.53° and 2.55°, for the 30° and 50° angles, respectively. Again, comparing the 20° with the 30° results (2.8° vs. 1.53°), and the 45° with the 70° (2.5° vs. 2.55°), differences higher than 1° are seen in the extreme angles, but similar values are observed for the intermediate ones. About this specific test, it is important to note that Lee and Lim (2023) used a box to slightly flex the knee and hip joints and to relax the unsupported leg, which raises questions about whether the load was completely transferred to the assessed leg and if there was a real unipedal test.

For the prone tests, the values for the 20°/45° angles were 4.0°/4.8° for the concentric repositioning test; and 4.8°/4.9° for the eccentric repositioning test, respectively. Clark et al. (2016) reported AAE in concentric and eccentric repositionings in the prone position to the 45° angle, although the aim of the study was not related to establishing normative values. These authors reported an AAE of 4.70° and 5.97° for concentric and eccentric repositioning, respectively. The values for the concentric repositioning are quite comparable (4.8° vs. 4.70°), while the results for the eccentric repositioning demark a difference higher than 1° (4.9° vs. 5.97°). The smaller sample size ($n = 12$) in the study of Clark et al. (2016) suggests the need for caution in these comparisons, besides that the comparison with extreme angles is not available.

Regarding the bipedal tests, the obtained values for the 20°/45° angles were 4.3°/3.0°. As the above-mentioned research, the study of Ghiasi and Akbari (2007) did not aim to report normative values, but rather to compare errors between weight-bearing and non-weight-bearing tests. Yet, an AAE for the intermediate angle of 45° of 3.6° was found, which is close to the present results (3.0° vs. 3.6°). As seen in other studies, the reported data of Ghiasi and Akbari (2007) are based on mean values and not median values obtained from 44 participants. Furthermore, values for extreme angles were not collected to allow a comparison to the 20° value.

Protocol-related factors of accuracy

The choice of the test position dictates whether the knee JPS assessments should be conducted under weight-bearing (closed kinetic chain) or non-weight-bearing conditions (open kinetic chain). Several authors defend that weight-bearing tests are more functional, better reproducing common functional activities such as gait, despite a component of open kinetic chain is also seen, particularly in the swing phase (Stillman & McMeeken, 2001).

Most studies describe that weight-bearing tests produce fewer errors compared to non-weight-bearing tests (Andersen et al., 1995; Herrington, 2005; Lephart et al., 1997; Stillman & McMeeken, 2001), since a larger contribution from mechanoreceptors of the surrounding joints (hip and ankle) and muscles reaches the CNS. Muscle mechanoreceptors (Golgi tendon organs and muscle spindles) are also described as being more activated when the lower limb is in weight-bearing (Andersen et al., 1995), as well as more motor units are recruited (Lee & Lim, 2023). This potentially results in a better representation of the knee position in space, inducing better accuracy to reposition. However, in weight-bearing tests, as they involve a repositioning of the whole limb, it is not possible to isolate the knee joint proprioceptive acuity (Stillman & McMeeken, 2001). This makes the non-weight-bearing tests more suitable for an early-stage monitoring of knee injury rehabilitation, when a more targeted assessment of a specific joint is desired. Furthermore, when performed in unipedal support, weight-bearing tests

may not be practical for individuals with balance deficits or pain during weight-bearing activities (Ghiasi & Akbari, 2007).

The present study investigated the magnitude of errors in three test positions, two of them consisting of non-weight-bearing tests (sitting and prone) and one in weight-bearing (standing). The results revealed that, as previously discussed, the standing position tests produced lower AAE (2.9°) than the sitting (3.1°) and prone (4.8°), although significant differences were only found in comparison with the prone position. These results align with the previous research of Ghiasi and Akbari (2007), in which the knee JPS was tested in the prone position and the standing position, particularly describing a bipedal squat, and better accuracy was found for the standing test.

Regarding the comparison between sitting and standing tests, Lee and Lim (2023) similarly described no significant differences between the AAE in these two positions, despite slightly higher errors in the sitting position, which was also seen in the present results, but without statistical significance. Nevertheless, a previous study comparing the AAE in sitting and standing positions also reported that the standing position produced significantly lower errors (Drouin et al., 2003).

In the present results, the AAE in the prone position were also significantly higher than those in the sitting position. These results are in line with the conclusions of Olsson et al. (2004), who described higher errors in the prone position. These authors also investigated the test-retest reliability of prone and sitting tests to assess the knee JPS, observing higher reliability for sitting tests (good to excellent), suggesting that the knee JPS should preferably be assessed in a sitting position rather than in a prone position, whose reliability only varied between fair to good. It has also been proposed that the prone position may be less comfortable, possibly explaining the higher errors and lower reliability (Olsson et al., 2004). All of this shows that the prone position may not be the most appropriate if a non-weight-bearing assessment is required.

This study also assessed differences in accuracy when describing concentric and eccentric repositionings in sitting and prone position tests. Effectively, a recent systematic review found that most studies assessing knee JPS focus on

concentric repositionings (Azevedo, Moreira-Silva, et al., 2024). However, it has been demonstrated that eccentric motions induce greater stimuli on the muscle spindles (Pickard et al., 2003), which, in theory, could increase the accuracy of reproducing the demonstrated angles. Nevertheless, the present results suggest no differences in the repositioning errors between the two types of repositionings.

Relph and Herrington (2016) assessed their participants' knee JPS in the sitting position for two knee motion directions, to extension and flexion, corresponding to concentric and eccentric repositionings, respectively. However, contrary to the present results, the eccentric repositioning (to flexion) produced significantly higher errors. The authors attributed this to the fact that the target angle for the eccentric repositioning test requested a shorter lever arm and probably required less neuromuscular control. It is worth noting that the protocol of knee JPS involved testing random angles within defined intermediate ranges, which is opposite to the fixed determined angles of this investigation. Nevertheless, the study of Haggerty et al. (2021), contrary to the authors' hypothesis, also found significantly higher errors when performing an eccentric repositioning to a 20° angle.

Different accuracies were verified when repositioning to the intermediate angle of 45° and the extreme angle of 20°. Joint mechanoreceptors send afferent information about joint position only at extreme ranges of the knee ROM (Proske, 2023; Riemann & Lephart, 2002). In contrast, muscle mechanoreceptors are more active at intermediate ranges (Docherty et al., 1998), especially between 40° and 80° of knee flexion (Olsson et al., 2004). However, the muscle spindle is described as a muscle mechanoreceptor that, as a stretch occurs, is able to provide positional information throughout the entire ROM of a joint (Proske, 2023). Accordingly, there is a cumulative contribution from joint and muscle mechanoreceptors at extreme ranges (Lee et al., 2003), and therefore, better proprioceptive acuity is expected at these ranges compared to intermediate ones, where the contribution is exclusively from muscle mechanoreceptors.

The previous assumption was confirmed for the sitting and prone position tests, but the opposite was found in the standing position tests. Indeed, in the sitting

and prone position tests, higher repositioning errors were observed in the intermediate angle (45°), while in the standing position tests, this was the target angle with lower errors. As previously discussed, in weight-bearing tests, there is a contribution from muscles with functions beyond the knee joint. Since muscle spindles are stretching detectors (Proske, 2023), the participant is forced to squat lower to reach the 45° angle than to reach the 20° angle, meaning that the degree of stretching of those involved muscles is greater when repositioning to 45° than to 20°. It is possible that the firing frequency of spindles increases when the stretch range is greater, which has been previously demonstrated in animal studies (Shepherd, 1965), and probably explains the presented results for the weight-bearing tests.

Differences in accuracy to reposition between target angles were previously investigated by Ghiasi and Akbari (2007), who, contrary to the present findings, reported no significant differences in the AAE between the tested target angles (45°, 60°, and 90°). However, since only target angles corresponding to intermediate ranges of the knee ROM were tested, considerable differences would not be expected, as the contribution in these angles would be exclusively from muscle mechanoreceptors. Finally, in line with our results, Olsson et al. (2004) also confirmed lower errors in extreme angles both in the sitting (30°) and prone positions (100°), compared to intermediate angles (40°, 50°, and 70°).

Based on the obtained results, although extreme and intermediate angles target different mechanoreceptors, and are therefore both relevant to assess, it appears that in non-weight-bearing tests, the use of extreme angles (such as 20°) is more favourable for minimizing repositioning errors, while in weight-bearing tests, intermediate angles (such as 45°) appear to lead to higher accuracy. These results reinforce the need to adapt the selection of the target angle and the type of weight-bearing to the intended clinical aim.

Influence of individual factors

Regarding individual factors, the present results suggest that neither sex nor dominance have an influence on the knee JPS. Different investigations have confirmed a significant fluctuation of the knee JPS across the menstrual cycle in female athletes (Fouladi et al., 2012) and non-athletes (Aydoğ et al., 2005), both concluding that the knee JPS is significantly reduced in the menstruation period. This observed fluctuation throughout the menstrual cycle could lead to differences in proprioceptive acuity between males and females. However, the results of the present study reinforce the conclusions of previous studies in non-weight-bearing (Azevedo et al., 2021; Busch et al., 2023) and weight-bearing conditions (Ghiasi & Akbari, 2007; Herrington, 2005), where an absence of differences in the knee JPS related to sex has been reported, proposing that this may not be a relevant factor when selecting participants for studies involving these assessments.

About dominance, although gait depends on the similar involvement of both limbs, in some daily-life or sport contexts, it is accepted that the dominant limb is preferably used in more dynamic tasks and gestures, while the non-dominant is used more for stabilization or support functions (Fousekis et al., 2010; Teixeira et al., 2011). Previous studies also show that the number of injuries between the two limbs is not similar, with the dominant limb being described as the most-injured one (DeLang et al., 2021). Despite this, the results of this study suggest a similar JPS between limbs, which is in line with prior findings in trained individuals (Azevedo et al., 2021; Muaidi et al., 2009). Despite the individuals of the present sample not being involved in sports practice, it is worth emphasizing that 80.6% were considered as having either a moderate or high level of physical activity. On the contrary, it has also been reported significantly lower repositioning errors in the dominant limb of non-trained individuals, who, according to the authors, were considered to have low levels of physical activity (Azevedo et al., 2021). Thus, the level of physical activity may be a confounding factor when assessing the influence of dominance on the knee JPS, which deserves further investigation.

Limitations

Some limitations of the study must be recognized. First, the calculation of the necessary sample size was not performed, and effectively, the achieved sample size may not guarantee robustness to the presented results. Nevertheless, these results are based on larger samples than those of studies also reporting normative values, for which the optimal sample size was calculated. Second, as only young individuals were assessed, it is not possible to extrapolate these results to other age groups.

Conclusions

This study provides normative data covering different knee JPS assessments in healthy young individuals, which may help clinicians to identify and monitor individuals with proprioceptive deficits. Considering the 20°/45° angles, the obtained normative values for the sitting position tests were 3.0°/3.7° for a concentric repositioning test, and 2.7°/3.6° for an eccentric repositioning test. In prone tests, the values for the concentric repositioning were 4.0°/4.8°, and 4.8°/4.9° for the eccentric repositioning test. Regarding standing position tests, the values of 2.8°/2.5° were obtained for the unipedal test, and 4.3°/3.0° for the bipedal test.

Regarding the influence of protocol-related and individual factors on the proprioceptive accuracy, the present results revealed:

- An influence of the test position, with the assessments in the prone position leading to worse accuracy, and the sitting and standing tests leading to better accuracy;
- No influence of the type of repositioning (concentric and eccentric), producing similar repositioning errors;

- An influence related to the chosen target angles, with the accuracy being better in extreme angles of sitting and prone position assessments, and in intermediate angles of standing position assessments;
- No influence of dominance, suggesting no need to assess both lower limbs as they appear to have the same acuity;
- No influence of sex, suggesting that this may not be a relevant factor when selecting participants for studies involving these assessments.

Future studies may reproduce the assessed tests with more robust samples, and considering more age groups, in order to provide normative values for all individuals.

References

- Andersen, S. B., Terwilliger, D. M., & Denegar, C. R. (1995). Comparison of Open versus Closed Kinetic Chain Test Positions for Measuring Joint Position Sense. *Journal of sport rehabilitation*, 4(3), 165-171. <https://doi.org/10.1123/jsr.4.3.165>
- Aydoğ, S. T., Hasçelik, Z., Demirel, H. A., Tetik, O., Aydoğ, E., & Doral, M. N. (2005). The effects of menstrual cycle on the knee joint position sense: preliminary study. *Knee Surgery, Sports Traumatology, Arthroscopy*, 13, 649-653. <https://doi.org/10.1007/s00167-004-0604-7>
- Azevedo, J., Moreira-Silva, I., Seixas, A., Fonseca, P., Oliveira, J., & Vilas-Boas, J. P. (2024). The Effect of Muscle Fatigue on the Knee Proprioception: A Systematic Review. *Journal of motor behavior*, 56(5), 772-804. <https://doi.org/10.1080/00222895.2024.2341753>
- Azevedo, J., Rodrigues, S., Moreira-Silva, I., Cardoso, R., & Seixas, A. (2024). Acute effects of muscle fatigue on the knee joint-position sense of trained and non-trained individuals. *Athena Health & Research Journal*, 1(1). <https://doi.org/10.62741/ahrj.v1i1.8>
- Azevedo, J., Rodrigues, S., & Seixas, A. (2021). The influence of sports practice, dominance and gender on the knee joint position sense. *The Knee*, 28, 117-123. <https://doi.org/10.1016/j.knee.2020.11.013>
- Barrett, D. S., Cobb, A. G., & Bentley, G. (1991). Joint proprioception in normal, osteoarthritic and replaced knees. *The Journal of bone and joint surgery. British volume*, 73(1), 53-56. <https://doi.org/10.1302/0301-620X.73B1.1991775>
- Bennell, K., Wee, E., Crossley, K., Stillman, B., & Hodges, P. (2005). Effects of experimentally-induced anterior knee pain on knee joint position sense in healthy individuals. *J. Orthop. Res.*, 23(1), 46-53. <https://doi.org/10.1016/j.orthres.2004.06.008>

- Busch, A., Bangerter, C., Mayer, F., & Baur, H. (2023). Reliability of the active knee joint position sense test and influence of limb dominance and sex. *Scientific Reports*, 13(1), 152. <https://doi.org/10.1038/s41598-022-26932-2>
- Clark, N. C., Akins, J. S., Heebner, N. R., Sell, T. C., Abt, J. P., Lovalekar, M., & Lephart, S. M. (2016). Reliability and measurement precision of concentric-to-isometric and eccentric-to-isometric knee active joint position sense tests in uninjured physically active adults. *Physical Therapy in Sport*, 18, 38-45. <https://doi.org/10.1016/j.ptsp.2015.06.005>
- Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Routledge. <https://doi.org/10.4324/9780203771587>
- DeLang, M. D., Salamh, P. A., Farooq, A., Tabben, M., Whiteley, R., van Dyk, N., & Chamari, K. (2021). The dominant leg is more likely to get injured in soccer players: systematic review and meta-analysis. *Biology of Sport*, 38(3), 397-435. <https://doi.org/10.5114/biolsport.2021.100265>
- Docherty, C. L., Moore, J. H., & Arnold, B. L. (1998). Effects of strength training on strength development and joint position sense in functionally unstable ankles. *J. Athl. Train.*, 33(4), 310-314. <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1320579/pdf/jathtrain00012-0016.pdf>
- Drouin, J. M., Houghlum, P. A., Perrin, D. H., & Gansneder, B. M. (2003). Weight-Bearing and Non-Weight-Bearing Knee-Joint Reposition Sense and Functional Performance. *Journal of sport rehabilitation*, 12(1), 54-66. <https://doi.org/10.1123/jsr.12.1.54>
- Fouladi, R., Rajabi, R., Naseri, N., Pourkazemi, F., & Geranmayeh, M. (2012). Menstrual cycle and knee joint position sense in healthy female athletes. *Knee Surgery, Sports Traumatology, Arthroscopy*, 20(8), 1647-1652. <https://doi.org/10.1007/s00167-011-1811-7>
- Fousekis, K., Tsepis, E., & Vagenas, G. (2010). Lower limb strength in professional soccer players: profile, asymmetry, and training age. *Journal*

- of sports science & medicine*, 9(3), 364-373.
<https://pmc.ncbi.nlm.nih.gov/articles/PMC3761700/pdf/jssm-09-364.pdf>
- Gear, W. S. (2011). Effect of different levels of localized muscle fatigue on knee position sense. *Journal of Sports Science and Medicine*, 10(4), 725-730.
<https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3761499/pdf/jssm-10-725.pdf>
- Ghiasi, F., & Akbari, A. (2007). Comparison of the effects of open and closed kinematic chain and different target position on the knee joint position sense. *J Med Sci*, 7(6), 969-976.
<https://doi.org/10.3923/jms.2007.969.976>
- Haggerty, A. L., Simon, J. E., Grooms, D. R., & Russell, J. A. (2021). Effect of Load, Angle, and Contraction Type on Clinically Assessed Knee Joint Position Sense. *Journal of sport rehabilitation*, 30(8), 1166-1171.
<https://doi.org/10.1123/jsr.2020-0552>
- Herrington, L. (2005). Knee-Joint Position Sense: The Relationship between Open and Closed Kinetic Chain Tests. *Journal of sport rehabilitation*, 14(4), 356-362. <https://doi.org/10.1123/jsr.14.4.356>
- IPAQ Research Committee. (2005). Guidelines for data processing and analysis of the International Physical Activity Questionnaire (IPAQ)-short and long forms. https://www.physio-pedia.com/images/c/c7/Quidelines_for_interpreting_the_IPAQ.pdf
- Itokazu, M. (2022). Reliability and accuracy of 2D lower limb joint angles during a standing-up motion for markerless motion analysis software using deep learning. *Medicine in Novel Technology and Devices*, 16, 100188.
<https://doi.org/10.1016/j.medntd.2022.100188>
- Ju, Y. Y., Wang, C. W., & Cheng, H. Y. K. (2010). Effects of active fatiguing movement versus passive repetitive movement on knee proprioception. *Clinical biomechanics*, 25(7), 708-712.
<https://doi.org/10.1016/j.clinbiomech.2010.04.017>

- LaStayo, P. C., Woolf, J. M., Lewek, M. D., Snyder-Mackler, L., Reich, T., & Lindstedt, S. L. (2003). Eccentric muscle contractions: their contribution to injury, prevention, rehabilitation, and sport. *Journal of Orthopaedic & Sports Physical Therapy*, 33(10), 557-571. <https://doi.org/10.2519/jospt.2003.33.10.557>
- Lau, K. K. L., Kwan, K. Y. H., Cheung, J. P. Y., Law, K. K. P., Wong, A. Y. L., Chow, D. H. K., & Cheung, K. M. C. (2024). Normative values of spinal and peripheral proprioception in position sense among healthy adolescents and young adults. *Scientific Reports*, 14(1), 31722. <https://doi.org/10.1038/s41598-024-82100-8>
- Lee, H.-M., Liao, J.-J., Cheng, C.-K., Tan, C.-M., & Shih, J.-T. (2003). Evaluation of shoulder proprioception following muscle fatigue. *Clinical biomechanics*, 18(9), 843-847. [https://doi.org/10.1016/S0268-0033\(03\)00151-7](https://doi.org/10.1016/S0268-0033(03)00151-7)
- Lee, Y., & Lim, C. (2023). Reference value of knee position sense in weight-bearing and non-weight-bearing conditions. *Knee Surgery & Related Research*, 35(1), 25. <https://doi.org/10.1186/s43019-023-00199-x>
- Lephart, S. M., Pincivero, D. M., Girardo, J. L., & Fu, F. H. (1997). The role of proprioception in the management and rehabilitation of athletic injuries. *The American journal of sports medicine*, 25(1), 130-137. <https://doi.org/10.1177/036354659702500126>
- Lokhande, M. V., Shetye, J., Mehta, A., & Deo, M. V. (2013). Assessment of knee joint proprioception in weight bearing and in non-weight bearing positions in normal subjects. *Journal of Krishna Institute of Medical Sciences University*, 2(2), 94-101. <https://www.jkimsu.com/jkimsu-vol2no2/jkimsu%20vol%20%20no%20%20july%20-%20dec%202013%2094-101.pdf>
- Muaidi, Q., Nicholson, L., & Refshauge, K. (2009). Do elite athletes exhibit enhanced proprioceptive acuity, range and strength of knee rotation compared with non-athletes? *Scandinavian journal of medicine & science*

in *sports*, 19(1), 103-112. <https://doi.org/10.1111/j.1600-0838.2008.00783.x>

Olsson, L., Lund, H., Henriksen, M., Rogind, H., Bliddal, H., & Danneskiold-Samsøe, B. (2004). Test–retest reliability of a knee joint position sense measurement method in sitting and prone position. *Adv. Physiother.*, 6(1), 37-47. <https://doi.org/10.1080/14038190310009894>

Pickard, C. M., Sullivan, P. E., Allison, G. T., & Singer, K. P. (2003). Is there a difference in hip joint position sense between young and older groups? *J Gerontol A Biol Sci Med Sci.*, 58(7), 631-635. <https://doi.org/10.1093/gerona/58.7.M631>

Proske, U. (2023). A reassessment of the role of joint receptors in human position sense. *Exp. Brain Res.*, 241(4), 943-949. <https://doi.org/10.1007/s00221-023-06582-0>

Relph, N., & Herrington, L. (2015). Criterion-related validity of knee joint-position-sense measurement using image capture and isokinetic dynamometry. *Journal of sport rehabilitation*, 24(1). <https://doi.org/10.1123/jsr.2013-0119>

Relph, N., & Herrington, L. (2016). The effects of knee direction, physical activity and age on knee joint position sense. *The Knee*, 23(3), 393-398. <https://doi.org/http://dx.doi.org/10.1016/j.knee.2016.02.018>

Riemann, B. L., & Lephart, S. M. (2002). The sensorimotor system, part I: the physiologic basis of functional joint stability. *Journal of athletic training*, 37(1), 71-79. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC164311/pdf/attr_37_01_0071.pdf

Riemann, B. L., Myers, J. B., & Lephart, S. M. (2002). Sensorimotor system measurement techniques. *J. Athl. Train.*, 37(1), 85-98. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC164313/pdf/attr_37_01_0085.pdf

- Rosenthal, R. (1991). Meta-analytic procedures for social research. In: SAGE Publications, Inc.
- Salgado, E., Ribeiro, F., & Oliveira, J. (2015). Joint-position sense is altered by football pre-participation warm-up exercise and match induced fatigue. *The Knee*, 22(3), 243-248. <https://doi.org/10.1016/j.knee.2014.10.002>
- Shepherd, G. (1965). Response of the isolated muscle spindle to different rates of stretching. Cold Spring Harbor Symposia on Quantitative Biology,
- Stillman, B. C., & McMeeken, J. M. (2001). The role of weightbearing in the clinical assessment of knee joint position sense. *Australian Journal of Physiotherapy*, 47(4), 247-253. [https://doi.org/https://doi.org/10.1016/S0004-9514\(14\)60272-5](https://doi.org/https://doi.org/10.1016/S0004-9514(14)60272-5)
- Teixeira, L. A., De Oliveira, D. L., Romano, R. G., & Correa, S. C. (2011). Leg preference and interlateral asymmetry of balance stability in soccer players. *Research quarterly for exercise and sport*, 82(1), 21-27. <https://doi.org/https://doi.org/10.1080/02701367.2011.10599718>
- Vandenbroucke, J. P., von Elm, E., Altman, D. G., Gøtzsche, P. C., Mulrow, C. D., Pocock, S. J., Poole, C., Schlesselman, J. J., Egger, M., & Initiative, f. t. S. (2007). Strengthening the Reporting of Observational Studies in Epidemiology (STROBE): Explanation and Elaboration. *Epidemiology*, 18(6), 805-835. <https://doi.org/10.1097/EDE.0b013e3181577511>

Chapter 4

Is the knee joint-position sense affected by different concentric or eccentric fatigue protocols of the quadriceps or hamstrings? A randomized controlled crossover trial

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Abstract

Background: The effects of muscle fatigue on the knee joint-position sense (KJPS) present conflicting conclusions in the literature. This study aimed to investigate the effect of different isolated concentric or eccentric fatigue protocols of the quadriceps or hamstrings on the KJPS of healthy individuals.

Methods: A four-period block-randomized controlled crossover trial was conducted with 22 healthy males. All participants underwent a control condition (5-minute rest), and four fatigue protocols in random order: concentric of quadriceps (QD_CC) or hamstrings (HS_CC); and eccentric of quadriceps (QD_ECC) or hamstrings (HS_ECC) in an isokinetic dynamometer. Surface electromyography, torque, and power of the *vastus lateralis* and *biceps femoris* were acquired during these procedures. Absolute angular errors (AAE) were calculated before and after conditions, while assessing KJPS in four tests to 45° of knee flexion, through active concentric and eccentric repositioning, in sitting and prone positions.

Results: AAE increased after all fatigue protocols. However, significant changes were seen in the four KJPS tests only after the QD_CC fatigue protocol; in three tests following the QD_ECC; in two tests after the HS_CC; and in one test following the HS_ECC protocol ($p < 0.05$). In general, this was accompanied by a decrease in torque and power, as well as in the mean/peak EMG and median frequency.

Conclusion: Isolated concentric or eccentric fatigue protocols involving the quadriceps or hamstrings negatively affected the knee JPS. The decreased muscle activation, combined with the reduced ability to produce force and power after fatigue, can contribute to joint instability and injury.

Keywords: muscle fatigue; knee; joint position sense; proprioception; EMG; torque; power

Introduction

Joint position sense (JPS) is a sub-modality of proprioception that expresses the ability to memorize and reproduce a joint position, without using vision (Riemann et al., 2002). To ensure this ability, mechanoreceptors within the muscle, particularly muscle spindles, are described as the ones providing more information to the Central Nervous System (CNS) (Lephart et al., 1998; Proske, 2023), followed by the joint and cutaneous mechanoreceptors (Lephart et al., 1998). According to Proske (2023), muscle spindles provide afferent information through an entire range of motion. However, the muscle mechanoreceptors are known to be more active in intermediate ranges (Docherty et al., 1998), which in the knee should be assessed in the ranges between 40° and 80° of flexion (Olsson et al., 2004). Joint mechanoreceptors, however, seem to intervene only in the extreme ranges of motion (Proske, 2023; Riemann et al., 2002).

Muscle fatigue describes a condition in which the skeletal muscle fails to generate or sustain force and power due to peripheral and/or central factors (Gandevia, 2001; Rampichini et al., 2020). Peripherally, an accumulation of metabolites causing environmental acidosis occurs, such as lactate, inorganic phosphates, and hydrogen ions, responsible for the inhibition of the actin and myosin cross-bridges, thus reducing the contractile force (Boyas & Guével, 2011; Tornero-Aguilera et al., 2022). Centrally, there is a decrease in the muscle voluntary activation, linked to a reduced motor cortex output and a decrease in the frequency and synchronization of motoneurons. Consequently, motor units are either not recruited or do not fire often enough, not allowing muscle fibres to produce their maximum force (Boyas & Guével, 2011; Tornero-Aguilera et al., 2022). Also, the accumulation of serotonin, which occurs during intense exercise, can induce the sensation of fatigue, leading to loss of neural drive and of motor units' recruitment (Boyas & Guével, 2011; Tornero-Aguilera et al., 2022).

The CNS depends on adequate proprioceptive information from the mechanoreceptors so that the necessary neuromuscular responses can be generated, protecting against excessive motions in the knee joint and ensuring the joint's stability. However, the above-mentioned metabolic changes seen

within the muscle with peripheral fatigue have been reported to cause an impact on the muscle spindle's function, leading to an increase of its discharge threshold (Balestra et al., 1992; Gribble & Hertel, 2004; Pedersen et al., 1998; Voight et al., 1996). This may translate, for example, into an increased time until activation of the stabilizing muscles of the joint, decreasing the ability to resist impacts (Maqsood & Váczi, 2023; Nagai et al., 2018). This impairment can be seen in falls in daily life, as well as when landing after jumping or when changing directions, which are common gestures in many sports that often lead to knee injuries. Therefore, this shows that muscle fatigue can be deleterious for sports performance and daily life tasks.

Previous investigations have studied the effects of muscle fatigue on the knee JPS. However, conflicting conclusions are presented, with studies confirming its negative impact and others reporting no significant effects after muscle fatigue (Bersotti et al., 2022; Da Silva et al., 2021; Paschalis et al., 2010; Torres et al., 2010; Vila-Chã et al., 2011), which may be explained by many involved variables. First, there is great variability in the applied fatigue protocols, which can be localized or general. The localized protocols often include a single or several muscle groups, and can be performed through concentric, eccentric, or a combination of both contraction-mode exercises, which impact the knee JPS differently (Azevedo, Moreira-Silva, et al., 2024). Secondly, the participants of most studies consist of individuals involved in sports practice, being possible that many of those fatigue protocols are not suitable or intense enough to impact their knee JPS, as these may have more resistance to fatigue than non-trained individuals. In this context, it is also important to note that non-trained individuals have not been the focus of extensive research on this topic. Another limitation seen in a large part of the available studies is that muscle fatigue is not confirmed or quantified with objective measures, such as force decrease (Givoni et al., 2007) or surface electromyography (sEMG) (Chang et al., 2012). Effectively, the sEMG signal has been described to carry information related to muscle fatigue, as myoelectric manifestations can be seen in changes in the signal frequency and amplitude (Al-Mulla et al., 2012; Chang et al., 2012). Finally, despite adopting different test positions, with the sitting position being the most used, the existing

studies focus on concentric repositionings. However, it is reported that eccentric contractions generate stronger stimuli in the muscle spindles (LaStayo et al., 2003). Furthermore, these contractions are known to provide deceleration in rapid motions of the knee joint, as well as to help absorb impact forces in the joint, which protects from repeated trauma of the joint surfaces and, consequently, from degenerative injuries (LaStayo et al., 2003; Lewek et al., 2002). Therefore, the impact of muscle fatigue is still not known on knee JPS assessments whose repositionings are performed eccentrically.

To fill the above-mentioned gaps, this study aims to investigate the effect of different isolated concentric or eccentric fatigue protocols of the quadriceps or hamstrings on the knee JPS of healthy individuals. For this purpose, during the fatigue protocols, the involved muscles will be monitored with sEMG, and the force and power variation will be quantified to check for evidence of muscle fatigue. Additionally, knee JPS will be assessed in different test positions, and through concentric and eccentric repositionings, to understand whether a specific muscle fatigue protocol has a greater impact on a particular repositioning test.

Methods

Study Design and Participants

This study consisted of a four-block randomized controlled crossover trial, and was reported according to the Consolidated Standards of Reporting Trials (CONSORT) statement, an extension to randomised crossover trials (Dwan et al., 2019). The trial registration number in ClinicalTrials.gov is NCT06331221.

An a priori sample size estimation resulted in an optimal number of 16 participants to achieve 95% power with $\alpha = 0.05$ to detect statistical differences in the assessed variables, considering a Cohen's d medium effect size of 0.4. A convenience sample of 22 healthy individuals participated in the study.

Inclusion criteria were: (i) males aged between 18 and 30 years; (ii) without current or previous knee pathology or surgery; and (iii) with a low or moderate physical activity level. Excluded were those: (i) with cardiorespiratory pathologies that could prevent the performance of the muscle fatigue protocols, or with any neurological or vestibular pathologies that could affect JPS; (ii) with positive knee integrity tests (anterior drawer, Lachman's test, posterior drawer, valgus and varus stress tests); and (iii) taking any medication that could affect motor control (sedatives, anxiolytics, antibiotics, analgesics, anti-inflammatories or myorelaxants). Participants were also requested to avoid strenuous activities and alcohol intake in the 48 hours before each session. The knee integrity tests were assessed by an experienced physical therapist (J.A.). Medical history was self-reported by the participants, while the level of physical activity was quantified using the International Physical Activity Questionnaire (IPAQ) – Short Form. According to its processing and analysis guidelines (IPAQ Research Committee, 2005), participants were categorized into a low or moderate physical activity level.

All participants were further characterized in terms of their age, body mass, height, body mass index (BMI), and lower limb dominance, which was considered the preferred lower limb to kick a ball.

All participants underwent a control condition (5-minute rest), and four muscle fatigue protocols, performed in random order, and with a washout period of at least one week. Participants' first condition was defined by block randomization, which was generated on an online platform (Sealed Envelope Ltd, 2024). Data collections had seven months of duration (from November 2023 to May 2024), and took place at the Porto Biomechanics Laboratory – University of Porto, Portugal.

This research was approved by the Ethics Committee of the Faculty of Sport of the University of Porto (CEFADE 20/2022), on the 11th of July 2022. All participants gave their written consent to participate in the study and all procedures were conducted according to the Helsinki's Declaration.

Study Conditions

In the first visit to the lab, participants performed a control condition and one of the experimental conditions, consisting of four different muscle fatigue protocols. The remaining fatigue protocols were assessed in random order, with a washout period of at least one week (Ribeiro et al., 2011; Shokri et al., 2018), totalizing four sessions. All conditions were performed with the participant's dominant lower limb.

Both the control and experimental conditions (muscle fatigue protocols) were performed in a Biodex Medical Systems 4 isokinetic dynamometer (Biodex, Shirley, New York, USA), using the following procedures:

- Control (CON) – a 5-minute rest, with the participant seated on the isokinetic dynamometer chair;
- Concentric hamstrings fatigue protocol (HS_CC) - 30 consecutive maximal concentric contractions of hamstrings at 30°/s from 30° to 90° of knee flexion;
- Eccentric hamstrings fatigue protocol (HS_ECC) – 30 consecutive maximal eccentric contractions of the hamstrings at 30°/s from 90° to 30° of knee flexion;
- Concentric quadriceps fatigue protocol (QD_CC) - 40 consecutive maximal concentric contractions of quadriceps at 30°/s from the 90° to 30° of knee flexion;
- Eccentric quadriceps fatigue protocol (QD_ECC) – 40 consecutive maximal eccentric contractions of quadriceps at 30°/s from the 30° to 90° of knee flexion.

Before each condition, participants performed three attempts of a maximum voluntary isometric contraction (MVIC) of the quadriceps and hamstrings, at 60° of knee flexion (Da Silva et al., 2022). A 30-second rest period was observed between repetitions, and the best repetition of the three was considered.

Before initiating the protocols, the participants were given a previous explanation of the intended actions. Regarding QD_CC and HS_ECC protocols, after the desired contraction, participants were instructed to let the limb fall without exerting force and in favour of gravity, to exclusively maintain concentric and eccentric contractions, respectively. Regarding the QD_ECC and HS_CC protocols, following the intended contraction, the participants' leg was passively moved to extension by a researcher, being asked not to exert force during this phase of the protocols, and once again, to keep them exclusively eccentric and concentric, respectively. Fatigue protocols and MVIC were executed with verbal encouragement and visual feedback from the dynamometer screen to elicit the participants' maximum effort.

Knee Joint-Position Sense Assessments

Before (PRE) and immediately after (POST) the above-mentioned conditions, participants were submitted to four knee JPS assessments in the isokinetic dynamometer.

Knee JPS procedures were conducted with the participants blindfolded, barefoot, and in a silent environment. All assessments were performed in the dominant limb and followed an active and ipsilateral positioning and repositioning. The chosen target angle for all JPS tests was the intermediate position of 45° of knee flexion (Clark et al., 2016).

Knee JPS was assessed in two positions in non-weight bearing conditions: seated and prone. For each test position, a concentric and eccentric reposition was adopted according to the following instructions:

- Concentric repositioning in the seated position (SIT_CC) – starting from 90° of knee flexion, a concentric extension was performed until reaching the target angle of 45° of knee flexion (Figure 1);
- Eccentric repositioning in the seated position (SIT_ECC) – starting from full knee extension, an eccentric flexion was performed until reaching the target angle of 45° (Figure 2);

- Concentric repositioning in prone position (PRONE_CC) - starting from full knee extension, a concentric flexion was performed until reaching the target angle of 45° (Figure 3);
- Eccentric repositioning in prone position (PRONE_ECC) – starting from 90° of knee flexion, an eccentric extension was performed until reaching the target angle of 45° (Figure 4).

From the starting positions, the participants actively and slowly moved the leg to the target angle (active positioning). When the predefined angle was reached, the dynamometer's lever locked the position, allowing the participant to memorize that position for five seconds. Then, they had to return to the starting position and, immediately after, actively reposition to the previously demonstrated target position. The participant verbalized when the target position was achieved, and an assessor recorded the current angle measured by the isokinetic dynamometer. Three attempts were given, and the average of the three was then considered (Salgado et al., 2015).

Randomization of the test position order (sitting or prone) was carried out, as well as of the type of repositioning (concentric or eccentric).

After these tests, repositioning errors were calculated and expressed as the absolute angular error (AAE), defined as the absolute value of the difference between the target and the achieved position by the participant (Bennell et al., 2005).



Figure 1. JPS procedures for the SIT_CC test: (A) describes the starting position (90° of knee flexion), and (B) the leg positioned at the target angle (45° of knee flexion).



Figure 2. JPS procedures for the SIT_ECC test: (A) describes the starting position (full knee extension), and (B) the leg positioned at the target angle (45° of knee flexion).

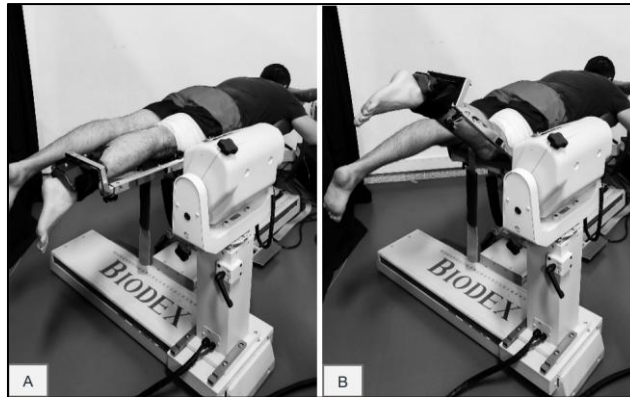


Figure 3. JPS procedures for the PRONE_CC test: (A) describes the starting position (full knee extension), and (B) the leg positioned at the target angle (45° of knee flexion).

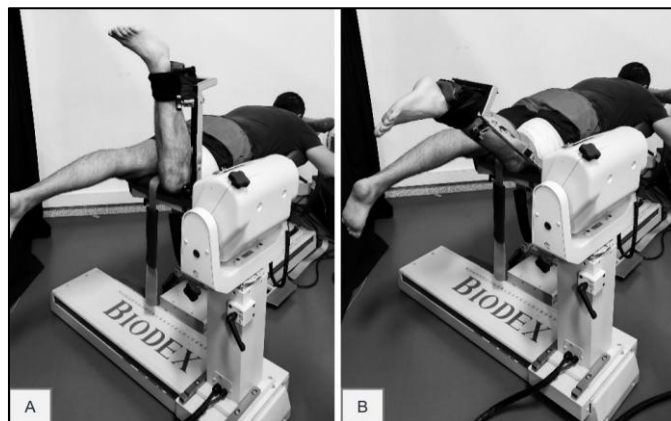


Figure 4. JPS procedures for the PRONE_ECC test: (A) describes the starting position (90° of knee flexion), and (B) the leg positioned at the target angle (45° of knee flexion).

Surface EMG Acquisitions

Surface EMG data were recorded during the MVIC and fatigue protocols, using two sEMG Galileo sensors (Delsys, Natick, USA). The sensory head of these sensors was placed over the *vastus lateralis* and *biceps femoris* muscles, as representatives of the quadriceps and hamstrings muscle groups (Aragão et al., 2015; Baroni et al., 2013). Before sensor placement, the skin was prepared, which involved shaving, abrasion, and cleaning with cotton soaked in alcohol. Sensors were then fixed on dry skin, considering the SENIAM recommendations for sensor placement (Hermens et al., 2000) over the belly of the referred muscles, respecting the direction of the muscle fibres. On the *vastus lateralis* muscle, the sensor's head was placed at a distance of 2/3 from the anterosuperior iliac spine and the lateral side of the patella, while the main body was positioned parallel with the sensor's head but posteriorly on the thigh. In the *biceps femoris*, the sensor's head was fixed at a middle distance between the ischial tuberosity and the lateral epicondyle of the tibia, and the sensor's main body was also arranged parallel with the sensor's head and anteriorly in the thigh.

Additionally, a Delsys Analog Sensor (Delsys Inc., Boston, MA, USA) was used to synchronously collect the data from the isokinetic dynamometer. Data recording was performed using the Delsys EMGWorks 4.8.0 software (Delsys Inc., Boston, MA, USA), at a sampling frequency of 2222 Hz (EMG) and 518 Hz (dynamometric data). An initial inspection of the EMG channels was performed to analyse the presence of excessive baseline noise, which should not exceed 10 μ V (Macgregor & Hunter, 2018).

Data Processing

A custom MATLAB R2024b script (Mathworks, Natick, MA, USA) was written to process the EMG and dynamometric data.

A single channel from each Galileo sensor was selected and used for further analysis. All EMG signals were band-pass filtered between 20-450 Hz with a second-order bidirectional Butterworth filter, full-wave rectified, and had their

root-mean-square (RMS) envelope calculated with a 100 ms window. All EMG data were subsequently normalized to the maximum activation of the corresponding muscle MVIC. Torque data was low-pass filtered at 100 Hz, and angular velocity and angular position were low-pass filtered by a 6 Hz second-order bidirectional Butterworth filter. Power was calculated as the product of torque and angular velocity.

For each fatigue protocol, the first and last muscle contractions were ignored. Then, the first and last group of three consecutive contractions were analysed. Within each group, contractions were individually analysed during their isokinetic period, as denoted by the dynamometer angular velocity. The mean and peak activation, as well as the median frequency of the muscle being fatigued were retrieved. For the same period, the mean and maximum torque and power were retrieved in absolute values, as well as normalized to the participant's body mass.

Statistical Analysis

Data analysis was performed using the software IBM SPSS v.26 for Windows. A significance level of 0.05 was considered for all analyses.

The normality of the variables' distribution was tested using the Shapiro-Wilk test. Since normality was not verified, continuous variables (age, body mass, height, BMI, AAE, torque, power, and EMG outcomes) were described in Median (Interquartile Range). Nominal variables (dominance and level of physical activity) were described as frequency (n) and percentage (%). Specifically for the repositioning errors analysis, a new variable was calculated (DIF), through the difference in the absolute errors between the assessment immediately after (POST) and before (PRE) the control or experimental conditions (assessment POST - assessment PRE). For this variable, positive values indicated higher errors after the respective condition (worsening), and negative values represented lower errors after the condition (improvement).

The Wilcoxon and Friedman's non-parametric tests were conducted. The Wilcoxon test was used for intragroup comparison of changes in AAE between

PRE and POST control or fatigue conditions; and to compare torque, power, and EMG outcomes between the first and last group of three contractions of the muscle fatigue protocols. Friedman's test was used for intergroup comparisons to verify the existence of differences in the AAE between conditions in the assessments PRE and POST control or fatigue conditions.

Results

Twenty-one participants successfully completed all conditions of the study. One participant was lost to follow-up (4.6% dropout rate) after the first session due to a knee injury during the washout period (Figure 5).

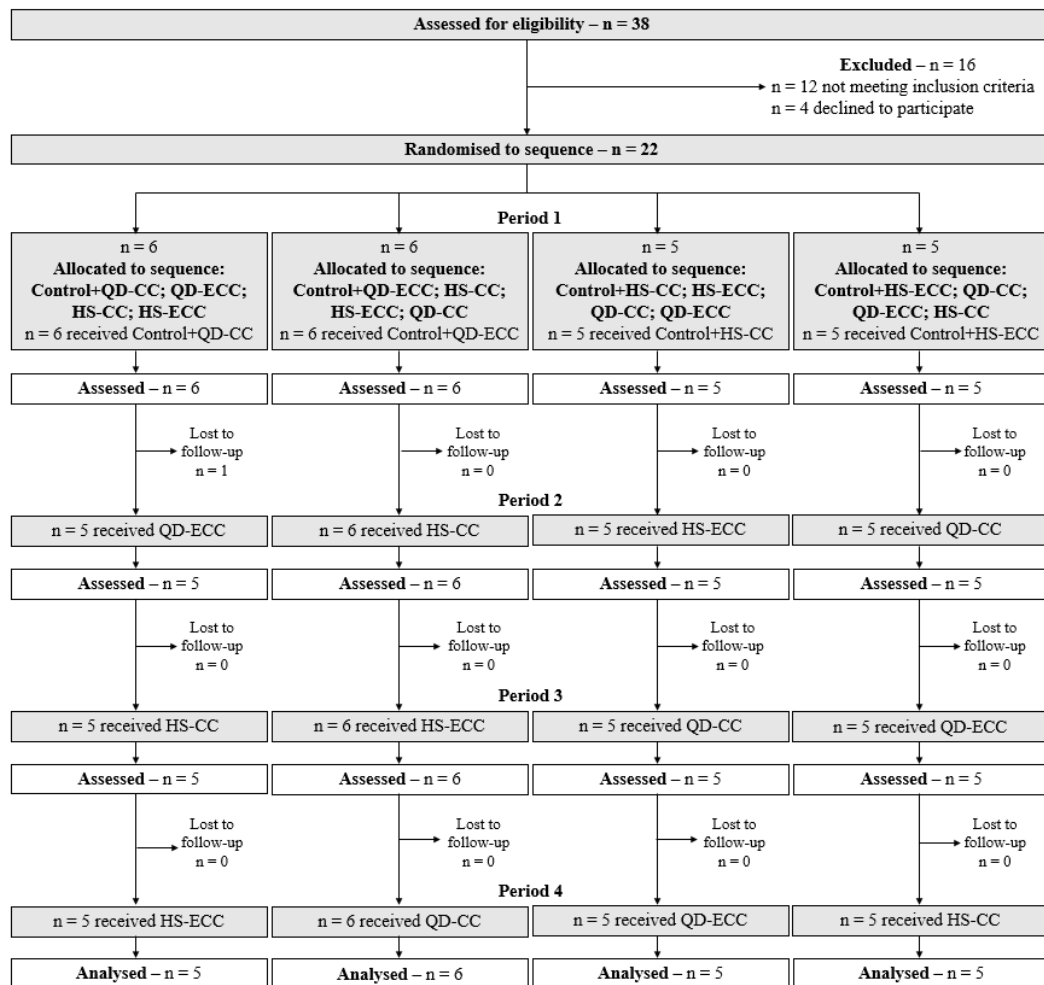


Figure 5. CONSORT flow diagram for crossover trials.

Regarding sample characterization, participants presented 23 (5) years of age, 72.9 (8.8) kg of body mass, 1.76 (0.10) m of height, and 24.3 (2.0) kg/m² of BMI. Pre-fatigue assessments revealed that participants reached an MVIC of 237 (40) N for the quadriceps and of 134 (42) N for the hamstrings.

The right lower limb was found to be the dominant limb in 17 participants (81.0%), and the left in 4 participants (19.0%). According to the IPAQ questionnaire, 11 participants were categorized as having a low physical activity level (52.4%), and the remaining 10 with a moderate level (47.6%)

Regarding AAE (Table 1), no significant differences were found in the Control Condition (CON) between the PRE and POST assessments in the four different JPS tests ($p > 0.05$). The HS_CC protocol registered a significant increase in the AAE after fatigue, evidencing a worsening in the repositioning accuracy in the SIT_ECC ($p = 0.042$) and PRONE_CC ($p = 0.009$) tests, while the other two tests also suggest an increase in the errors, although not significant. After the HS_ECC protocol, an increase in AAE is observed, despite only a statistically significant difference being verified for the SIT_ECC test ($p = 0.031$). The QD_CC protocol caused a significant increase in AAE in all four JPS tests (SIT_CC: $p = 0.009$; SIT_ECC: $p = 0.025$; PRONE_CC: $p = 0.010$; PRONE_ECC: $p = 0.002$), depicting a deterioration in the capacity of repositioning after this protocol. Finally, the QD_ECC protocol led to a significant increase of AAE in all tests (SIT_CC: $p = 0.029$; SIT_ECC: $p = 0.007$; PRONE_ECC: $p = 0.023$), except the PRONE_CC ($p = 0.433$). For all study conditions and JPS tests, the positive values presented by the variable DIF evidence a worsening in AAE between the PRE and POST assessments.

Table 1. Intra- and intergroup comparisons regarding AAE (in degrees) during knee JPS tests.

Position	Type of Repositioning	Condition	AAE			
			PRE ^a	POST ^a	DIF ^a	<i>p</i> ^b
SIT	CC	CON	3.3 (4.3)	5.0 (6.5)	1.7 (7.0)	0.348
		HS_CC	3.3 (3.5)	3.0 (5.3)	1.7 (3.7)	0.064
		HS_ECC	2.3 (5.8)	4.7 (5.8)	0.3 (3.7)	0.052
		QD_CC	2.3 (4.0)	3.7 (7.0)	2.0 (7.0)	0.009*
		QD_ECC	2.7 (3.5)	3.7 (5.3)	1.3 (3.8)	0.029*
		<i>p</i> ^c	0.778	0.916	0.757	
	ECC	CON	5.0 (6.5)	5.7 (8.5)	0.3 (7.0)	0.862
		HS_CC	3.0 (3.3)	3.4 (5.8)	2.0 (4.3)	0.042*
		HS_ECC	4.3 (4.5)	6.0 (8.2)	2.0 (6.5)	0.031*
		QD_CC	3.7 (4.2)	4.3 (8.0)	1.0 (4.7)	0.025*
		QD_ECC	2.7 (1.8)	5.3 (5.7)	2.7 (5.8)	0.007*
		<i>p</i> ^c	0.282	0.884	0.321	
PRONE	CC	CON	4.0 (5.3)	5.3 (7.3)	0.7 (7.3)	0.821
		HS_CC	3.0 (4.8)	6.0 (3.8)	3.3 (4.3)	0.009*
		HS_ECC	3.0 (3.5)	4.0 (6.8)	1.0 (5.7)	0.122
		QD_CC	3.0 (4.2)	5.7 (6.8)	1.3 (3.8)	0.010*
		QD_ECC	4.7 (3.7)	5.0 (7.8)	0.0 (4.5)	0.433
		<i>p</i> ^c	0.361	0.911	0.244	
	ECC	CON	4.3 (7.3)	8.3 (7.3)	2.7 (9.7)	0.089
		HS_CC	4.3 (5.5)	6.0 (9.0)	1.3 (5.3)	0.102
		HS_ECC	7.0 (7.8)	7.6 (7.8)	0.6 (3.8)	0.161
		QD_CC	5.0 (5.5)	8.0 (3.7)	3.0 (4.5)	0.002*
		QD_ECC	4.0 (4.7)	5.0 (7.7)	0.7 (5.5)	0.023*
		<i>p</i> ^c	0.145	0.474	0.512	

Notes: CC: concentric repositioning; ECC: eccentric repositioning; CON: Control; HS_CC: hamstrings concentric fatigue protocol; HS_ECC: hamstrings eccentric fatigue protocol; QD_CC: quadriceps concentric fatigue protocol; QD_ECC: quadriceps eccentric fatigue protocol; PRE: assessments before conditions; POST: assessments immediately after conditions; DIF: variation in repositioning errors between POST and PRE assessments; ^a Median (Interquartile Range); ^b Wilcoxon Test; ^c Friedman Test; * $p < 0.05$

Table 2 presents the torque and power results between the first and last three contractions of the four muscle fatigue protocols. The two concentric fatigue protocols (HS_CC and QD_CC) produced a significant decrease in all torque and power variables between the beginning and end of these protocols. The fatigue protocol HS_ECC led to a significant decrease in the mean torque ($p = 0.002$) and mean power ($p = 0.002$). Finally, the fatigue protocol QD_ECC did not evidence significant changes in any of the assessed torque or power variables ($p > 0.05$).

Specifically regarding significant peak torque decreases, the HS_CC and QD_CC fatigue protocols produced decreases of 25.1% and 21.0%, respectively. Regarding maximum power, the HS_CC and QD_CC fatigue protocols produced significant decreases of 22.9% and 20.7%, respectively.

Table 2. Torque and power results between the first (Beg.) and last (End) group of three contractions of the four muscle fatigue protocols.

Variable	Period	HS_CC	HS_ECC	QD_CC	QD_ECC
Mean Torque (N.m)	Beg. ^a	92.08 (36.96)	80.62 (30.33)	133.13 (44.71)	117.43 (5.93)
	End ^a	62.44 (14.55)	66.89 (21.05)	86.86 (26.16)	113.87 (31.53)
	p^c	<0.001*	0.002*	<0.001*	0.689
Mean Torque (N.m/kg)	Beg. ^a	1.24 (0.40)	1.04 (0.41)	1.84 (0.54)	1.56 (0.23)
	End ^a	0.82 (0.16)	0.89 (0.29)	1.29 (0.38)	1.50 (0.59)
	p^c	<0.001*	0.002*	<0.001*	0.702
Peak Torque (N.m)	Beg. ^a	111.11 (40.28)	98.73 (38.73)	171.07 (38.15)	158.32 (14.22)
	End ^a	83.16 (24.83)	88.70 (40.33)	135.22 (45.10)	168.96 (53.51)
	p^c	0.001*	0.092	0.004*	0.876
Peak Torque (N.m/kg)	Beg. ^a	1.52 (0.30)	1.28 (0.51)	2.37 (0.71)	2.11 (0.25)
	End ^a	1.13 (0.35)	1.18 (0.45)	1.82 (0.59)	2.10 (0.77)
	p^c	0.001*	0.073	0.003*	0.835
Mean Power (W)	Beg. ^a	51.29 (20.56)	42.74 (16.50)	73.41 (27.91)	60.00 (1.42)
	End ^a	34.50 (8.73)	35.40 (11.64)	53.39 (13.46)	57.99 (1.56)
	p^c	<0.001*	0.002*	<0.001*	0.689
Mean Power (W/kg)	Beg. ^a	0.69 (0.23)	0.55 (0.21)	1.02 (0.32)	0.82 (0.10)
	End ^a	0.46 (0.09)	0.47 (0.15)	0.71 (0.22)	0.80 (0.31)
	p^c	0.001*	0.002*	<0.001*	0.689

Table 2 (Cont.). Torque and power results between the first (Beg.) and last (End) group of three contractions of the four muscle fatigue protocols.

Variable	Period	HS_CC	HS_ECC	QD_CC	QD_ECC
Max. Power (W)	Beg. ^a	60.61 (22.60)	52.43 (20.83)	94.90 (22.59)	82.24 (5.44)
	End ^a	46.74 (13.78)	47.01 (22.13)	75.28 (25.31)	89.47 (24.99)
	p^c	0.001*	0.099	0.004*	0.794
Max. Power (W/kg)	Beg. ^a	0.83 (0.28)	0.68 (0.28)	1.31 (0.39)	1.10 (0.15)
	End ^a	0.64 (0.19)	0.63 (0.24)	1.01 (0.31)	1.12 (0.41)
	p^c	<0.001*	0.078	0.003*	0.876

Notes: Beg.: 3 first contractions of the protocol; End: 3 last contractions of the protocol; QD_CC: quadriceps concentric fatigue protocol; QD_ECC: quadriceps eccentric fatigue protocol; HS_CC: hamstrings concentric fatigue protocol; HS_ECC: hamstrings eccentric fatigue protocol; ^a Median (Interquartile Range); ^b Friedman Test; ^c Wilcoxon Test; * $p < 0.05$

Table 3 presents the EMG results between the first and last group of three contractions of the four fatigue protocols.

Regarding mean EMG, a significant decrease was only found between the beginning and the end of the eccentric fatigue protocols (HS_ECC: $p = 0.030$; QD_ECC: $p = 0.003$). On the other hand, despite a decreasing trend of peak EMG in all fatigue protocols, it only achieves significance in the QD_ECC protocol ($p = 0.002$).

Finally, the median frequency significantly decreased at the end of all protocols (HS_CC: $p < 0.001$; HS_ECC: $p = 0.001$; QD_CC: $p = 0.001$), except the QD_ECC ($p = 0.230$).

Table 3. EMG results between the first (Beg.) and last (End) group of three consecutive contractions of the four muscle fatigue protocols.

Variable	Period	HS_CC	HS_ECC	QD_CC	QD_ECC
Mean EMG (%MVIC)	Beg. ^a	42.70 (20.39)	40.79 (13.88)	44.49 (23.70)	32.82 (18.74)
	End ^a	36.47(24.28)	34.88 (17.18)	44.79 (26.37)	25.21 (22.24)
	<i>p</i> ^c	0.068	0.030*	0.566	0.003*
Peak EMG (%MVIC)	Beg. ^a	88.53 (39.04)	83.24 (31.43)	88.86 (40.40)	80.73 (46.53)
	End ^a	85.60 (58.85)	82.47 (39.52)	85.13 (51.05)	59.06 (41.41)
	<i>p</i> ^c	0.455	0.274	0.455	0.002*
Median Frequency (Hz)	Beg. ^a	74.40 (18.40)	77.80 (12.20)	63.20 (7.90)	60.00 (8.80)
	End ^a	62.10 (18.30)	72.40 (9.30)	58.10 (5.80)	58.70 (10.70)
	<i>p</i> ^c	<0.001*	0.001*	0.001*	0.230

Notes: Beg.: 3 first contractions of the protocol; End: 3 last contractions of the protocol; QD_CC: quadriceps concentric fatigue protocol; QD_ECC: quadriceps eccentric fatigue protocol; HS_CC: hamstrings concentric fatigue protocol; HS_ECC: hamstrings eccentric fatigue protocol; ^a Median (Interquartile Range); ^b Friedman Test; ^c Wilcoxon Test; * $p < 0.05$

Discussion

This study aimed to investigate the effect of different isolated concentric or eccentric fatigue protocols of the quadriceps or hamstrings on the knee JPS of healthy individuals.

The muscle fatigue protocols were all performed at the angular velocity of 30°/s. This angular velocity was previously used to assess the acute effects of muscle fatigue on different knee proprioceptive senses, with confirmed significant deleterious effects (Da Silva et al., 2022; Da Silva et al., 2021). Furthermore, it was previously described that muscle fatigue develops to a greater extent at slower angular velocities, such as 30°/s, when compared to higher velocities (Mathiassen, 1989).

Regarding the number of chosen contractions for the muscle fatigue protocols, Sangnier and Tourny-Chollet (2007) demonstrated that the force decline as a consequence of muscle fatigue differs between the quadriceps and hamstrings

muscle groups. Strength seems to decline more in the hamstrings group than in the quadriceps, which may be related to structural differences between the two muscles, particularly in the proportion of fast and slow-twitch muscle fibres (Lievens et al., 2020). For this reason, 40 contractions were chosen for the quadriceps fatigue protocols, and 30 contractions for the hamstrings' protocols.

The chosen target angle for the assessments was the intermediate position of 45° of knee flexion (Clark et al., 2016), where a greater activation of muscle mechanoreceptors has been described (Docherty et al., 1998; Olsson et al., 2004). Although some studies assess JPS at both intermediate and extreme ranges, a significant increase in repositioning errors is often reported only at the intermediate assessed angles (Ali et al., 2013; Azevedo, Rodrigues, et al., 2024), which suggests that the effects of muscle fatigue are, as expected, more pronounced on the muscle mechanoreceptors than on the joint ones. Nevertheless, other investigations have also described an increase in knee ligament laxity as a consequence of fatiguing exercise (Johannsen et al., 1989; Steiner et al., 1986), meaning that a disturbance of the information provided by the joint mechanoreceptors should not be disregarded. Additionally, according to Pickard et al. (2003), a higher accuracy in JPS is accomplished when the repositioning is preceded by an active muscle contraction, since it results in a pre-activation of the muscle mechanoreceptors. In that sense, all knee JPS tests in this study were conducted with both active positioning and repositioning. Clark et al. (2016) also defend that active tests are preferred over passive ones since these allow for more closely mimicking the functional conditions of the knee joint.

The results of the present study revealed that all four muscle fatigue protocols caused negative effects on the knee JPS, as seen by the increase in the repositioning errors. In fact, the QD_CC fatigue protocol was the one that produced a negative impact in a greater number of tests, since all four JPS tests registered significant increases in errors, followed by the QD_ECC fatigue protocol, which led to a significant increase in errors in three of the assessed JPS tests. The HS_CC and HS_ECC fatigue protocols only caused a significant increase in errors in two and one JPS test, respectively.

Regarding the QD_CC fatigue protocol, between the initial and final contractions, a significant torque (21.0%) and power (20.7%) decline was found, as well as a decrease in the median frequency recorded by sEMG, confirming that muscle fatigue has set in and produced a negative impact on the knee JPS. Recent studies involving concentric protocols of the knee extensors have shown conflicting conclusions about their effects on the knee JPS of healthy individuals (Bersotti et al., 2022; Kim et al., 2023). Both Bersotti et al. (2022) and Kim et al. (2023) assessed the ability to reposition to intermediate angles of the knee ROM, before and after fatigue protocols consisting of concentric knee extensions at 60°/s. However, despite of the similarities between the JPS assessment method and of the fatigue protocols, Kim et al. (2023) reported significantly higher repositioning errors after fatigue, while Bersotti et al. (2022) found no significant changes in the errors post-fatigue. Both studies also quantified the torque decrease between pre- and post-fatigue and confirmed a significant decline throughout the protocol, suggesting that fatigue was induced. Despite this, the repositioning errors in the study of Bersotti et al. (2022) remained unchanged, which was probably related to the adopted JPS familiarization process, in which the participants were instructed to repeat the repositionings as many times as necessary to be familiar with the JPS protocol, which may have induced a learning-effect, that possibly lasted even after fatigue.

Between the beginning and the end of the QD_ECC protocol, no significant differences consistent with a torque or power decrease were observed, which could suggest that the protocol was insufficient to cause fatigue. However, EMG results revealed a significant decrease in the mean and peak EMG between the initial and last contractions of this protocol, suggesting the presence of fatigue signs. Effectively, according to Al-Mulla et al. (2012), EMG can provide early indicators of fatigue, detecting it even before its onset, which can manifest as changes in the signal frequency and/or amplitude (Rampichini et al., 2020). As already discussed, there was a significant increase in AAE in three JPS tests (SIT_CC, SIT_ECC, and PRONE_ECC) after this protocol, suggesting the involvement of fatigue, which has produced a decline in the repositioning accuracy. Three previous studies investigated the effects of muscle fatigue

protocols involving eccentric knee extensions at 60°/s (Paschalis et al., 2007; Torres et al., 2010; Vila-Chã et al., 2011), and, consistent with our results, concluded that these protocols led to an impairment of knee JPS assessed in intermediate angles and non-weight bearing conditions. Besides the acute effects, Vila-Chã et al. (2011) and Torres et al. (2010) also reported that these effects even remained after 24 and 48 hours, respectively. Additionally, Vila-Chã et al. (2011) tested their participants' JPS in weight-bearing conditions, and, interestingly, JPS seemed unaffected both immediately after and 24 hours after fatigue, which was not consistent with the non-weight-bearing tests' conclusions. These results may suggest that, when performing repositionings in weight-bearing, other non-fatigued muscles with functions in the knee and other lower limb joints may compensate with increased input, mitigating the effects of muscle fatigue on the knee JPS, highlighting a crucial joint stability protection mechanism. Considering that these assessments are also conducted in a standing position, it cannot be disregarded a contribution from cutaneous mechanoreceptors compared to non-weight bearing tests. Indeed, studies to identify which knee JPS test positions and types of repositioning are most appropriate for achieving better accuracy are still needed.

Regarding the HS_CC fatigue protocol, significantly higher repositioning errors were observed in two JPS tests (SIT_ECC and PRONE_CC). This fatigue protocol produced a significant torque (25.1%) and power (22.9%) decrease, accompanied by a significantly lower EMG median frequency in the final repetitions, confirming the presence of muscle fatigue, which ultimately produced a worsening in the knee JPS. These results are corroborated by Allen et al. (2010), who, despite having used an alternative repositioning method to the one used in the present study (contralateral repositioning), found significant increases of errors when repositioning to the target angle of 45° of knee flexion after a concentric fatigue protocol of the knee flexors.

After the HS_ECC fatigue protocol, the AAE significantly increased only in the SIT_ECC JPS test. Effectively, comparing peak torque and maximum power at the beginning and at the end of this protocol, a decrease of only 10.2% and 10.3% was seen, respectively, and probably contributed to a slighter effect of JPS errors.

Nevertheless, after this protocol, a significant decrease in the mean torque and power, as well as in the mean EMG and median frequency, was also observed, probably justifying the impairment of AAE post-fatigue. It is important to note that the other JPS tests follow the same tendency of the SIT_ECC test, since, as observed by the variable DIF, there is always a positive value indicating a worsening post-fatigue. Similar to our results, Da Silva et al. (2023) have reported a significant increase in errors after an eccentric fatigue protocol for the knee flexors when repositioning to intermediate target positions. Besides the errors, a significant torque decrease, and a reduced ability to recruit the *biceps femoris* muscle as assessed by sEMG was also registered, which is also consistent with the presented results. The authors also assessed these variables 24 hours after the protocol but found that they all had returned to pre-fatigue values. Paschalis et al. (2010), also in line with our results, described a significant impairment in the knee JPS immediately after a fatigue protocol of five sets of 15 eccentric maximal contractions of the knee flexors at 60°/s. However, contrary to the results of Da Silva et al. (2023), the impairment remained for three days. Indeed, evidence of muscle damage with this protocol was reported, such as a significant increase in delayed-onset muscle soreness (DOMS) and creatine kinase blood concentration, as well as a decrease in isometric peak torque compared to baseline values. The results of Paschalis et al. (2010) suggest that the impacts of eccentric fatigue protocols on the knee JPS may go beyond the acute effects, due to possible induced muscle damage, making it relevant to assess whether these effects persist for longer periods.

Although the sense of position arises from the proprioceptive information from the agonist and antagonist muscles around the knee joint, considering the muscle spindle function of detecting muscle stretching (Kröger & Watkins, 2021), it is argued that more contribution comes from the muscle being stretched during that repositioning test. For example, when in the seated position and repositioning from knee flexion to extension, the muscle group being stretched are the knee flexors. In this context, it is hypothesized that, if this muscle group is fatigued, this would affect more a specific repositioning test, being expected higher errors in the SIT_CC and PRONE_ECC tests, as these depend on the stretching of the

hamstrings. However, this assumption was not confirmed by the present results. Indeed, isolated muscle fatigue protocols (either of the quadriceps or the hamstrings) were performed, and, after them, regardless of the fatigued muscle group, the repositioning errors show a similar affectation in the tests relying on the quadriceps or hamstrings stretching. In fact, in the post-fatigue assessment, the intergroup comparisons confirmed no significant differences between the four tested fatigue protocols regarding the performance in the assessed knee JPS. These results question whether it is necessary to use different repositioning tests when assessing the impact of different fatigue protocols. The conclusions of Ribeiro et al. (2011), in which fatigue was induced at separated times in the knee extensors and flexors, are in line with our results and reinforce the previous suggestion, as both protocols significantly increased repositioning errors when repositioning to knee extension, concluding that, regardless of the fatigued muscle group, a significant reduction on the knee repositioning accuracy to extension occurred. Nevertheless, it is important to emphasize that this comparison should be carried out cautiously, as the protocol of Ribeiro et al. (2011) consisted of both concentric and eccentric contractions, while the protocols of the present study were strictly concentric or eccentric. Either way, future research should focus on the respective contributions from the knee flexors and extensors to the repositioning ability, both in non-fatigued and fatigued conditions, namely, describing the coactivation of these muscle groups during different knee JPS tests, as well as the number and type of motor units activated, either through conventional or decomposition electromyography.

Some limitations of this study must be recognized. First, a crossover study design was chosen. Although this type of design ensures a lower within-patient variability, requiring fewer participants, there are also some disadvantages, such as possibly larger dropout rates and potential carry-over and learning effects. Nevertheless, the dropout rate of the study was low (4.6%), and to decrease the potential learning effect, randomization of the order of the experimental conditions was performed. Regarding the carry-over effect, a washout period between conditions of at least one week was observed to ensure the recovery of a fatigued state from the previous condition. Indeed, previous investigations

evidence recovery from muscle fatigue following isokinetic fatiguing exercise in shorter periods than one week (Byrne & Eston, 2002; Michaut et al., 2003). Second, the blinding of participants and assessors was not possible. Third, the control condition was the only condition that was not randomized and, effectively, was always the first condition for every participant, which puts the results of the control condition at a disadvantage compared to the remaining conditions. Finally, only the acute effects of muscle fatigue were assessed, so it is not possible to draw conclusions regarding how long the impairment on the knee JPS would remain.

Conclusions

The results of the present study reveal that the assessed fatigue protocols, involving isolated concentric or eccentric contractions of the quadriceps or hamstrings, produced negative effects on the knee JPS. Nevertheless, some muscle fatigue protocols produced significant effects on a greater number of JPS tests, with the concentric of the quadriceps fatigue protocol being the one that affected more tests, followed by the eccentric of the quadriceps, the concentric of the hamstrings, and, finally, the eccentric of the hamstrings.

It was also found that regardless of the fatigued muscle group, there was a similar effect in the performance of the assessed knee JPS tests. This suggests that, when it comes to assessing the impact of muscle fatigue protocols as these presented, it may not be necessary to assess the knee JPS in so many different test positions or types of repositioning.

In general, EMG results displayed a decrease in the mean and peak EMG as well as in the median frequency, evidencing decreased activation and consequently, decreased input after fatigue. This, combined with the also seen reduced ability to produce force and power, can ultimately contribute to joint instability and injury.

References

- Al-Mulla, M., Sepulveda, F., & Colley, M. (2012). sEMG techniques to detect and predict localised muscle fatigue. *EMG methods for evaluating muscle and nerve function*, 157-186.
- Ali, Y., Farzaneh, G., & Homayoon, A. (2013). The Effect Of Fatigue On The Ankle And Knee Proprioception And Dynamic Control Of Posture. *International Journal of Sports Sciences & Fitness*, 3(2), 235-249. <https://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=90508075&lang=pt-pt&site=ehost-live&scope=site>
- Allen, T., Leung, M., & Proske, U. (2010). The effect of fatigue from exercise on human limb position sense. *The Journal of physiology*, 588(8), 1369-1377. <https://doi.org/10.1113/jphysiol.2010.187732>
- Aragão, F. A., Schäfer, G. S., Albuquerque, C. E. d., Vituri, R. F., Azevedo, F. M. d., & Bertolini, G. R. F. (2015). Neuromuscular efficiency of the vastus lateralis and biceps femoris muscles in individuals with anterior cruciate ligament injuries. *Revista Brasileira de Ortopedia*, 50, 180-185. <https://doi.org/10.1016/j.rboe.2015.03.010>
- Azevedo, J., Moreira-Silva, I., Seixas, A., Fonseca, P., Oliveira, J., & Vilas-Boas, J. P. (2024). The Effect of Muscle Fatigue on the Knee Proprioception: A Systematic Review. *Journal of motor behavior*, 56(5), 772–804. <https://doi.org/10.1080/00222895.2024.2341753>
- Azevedo, J., Rodrigues, S., Moreira-Silva, I., Cardoso, R., & Seixas, A. (2024). Acute effects of muscle fatigue on the knee joint-position sense of trained and non-trained individuals. *Athena Health & Research Journal*, 1(1). <https://doi.org/10.62741/ahrj.v1i1.8>
- Balestra, C., Duchateau, J., & Hainaut, K. (1992). Effects of fatigue on the stretch reflex in a human muscle. *Electroencephalography and Clinical*

Neurophysiology/Evoked Potentials Section, 85(1), 46-52.
[https://doi.org/10.1016/0168-5597\(92\)90101-G](https://doi.org/10.1016/0168-5597(92)90101-G)

Baroni, B. M., Geremia, J. M., Rodrigues, R., De Azevedo Franke, R., Karamanidis, K., & Vaz, M. A. (2013). Muscle architecture adaptations to knee extensor eccentric training: rectus femoris vs. vastus lateralis. *Muscle & nerve*, 48(4), 498-506. <https://doi.org/10.1002/mus.23785>

Bennell, K., Wee, E., Crossley, K., Stillman, B., & Hodges, P. (2005). Effects of experimentally-induced anterior knee pain on knee joint position sense in healthy individuals. *J. Orthop. Res.*, 23(1), 46-53. <https://doi.org/10.1016/j.orthres.2004.06.008>

Bersotti, F. M., De Melo, T. B., Rafael Skau, J., Mochizuki, L., & Ervilha, U. F. (2022). Fatigue of knee extensor muscles does not alter knee joint position sense. *J. Mech. Med. Biol.*, 22(2), 2250012-2250011-2250012-2250019. <https://doi.org/10.1142/S0219519422500129>

Boyas, S., & Guével, A. (2011). Neuromuscular fatigue in healthy muscle: underlying factors and adaptation mechanisms. *Annals of physical and rehabilitation medicine*, 54(2), 88-108. <https://doi.org/10.1016/j.rehab.2011.01.001>

Byrne, C., & Eston, R. (2002). Maximal-intensity isometric and dynamic exercise performance after eccentric muscle actions. *Journal of sports sciences*, 20(12), 951-959. <https://doi.org/10.1080/026404102321011706>

Chang, K.-M., Liu, S.-H., & Wu, X.-H. (2012). A wireless sEMG recording system and its application to muscle fatigue detection. *Sensors*, 12(1), 489-499. <https://doi.org/10.3390/s120100489>

Clark, N. C., Akins, J. S., Heebner, N. R., Sell, T. C., Abt, J. P., Lovalekar, M., & Lephart, S. M. (2016). Reliability and measurement precision of concentric-to-isometric and eccentric-to-isometric knee active joint position sense tests in uninjured physically active adults. *Physical Therapy in Sport*, 18, 38-45. <https://doi.org/10.1016/j.ptsp.2015.06.005>

- Da Silva, F., Colson, S. S., Zghal, F., Chorin, F., Guérin, O., & Monjo, F. (2022). Immediate voluntary activation deficits following submaximal eccentric contractions of knee extensors are associated with alterations of the sense of movement. *Scientific Reports*, 12(1), 1-10. <https://doi.org/10.1038/s41598-022-06081-2>
- Da Silva, F., Monjo, F., Zghal, F., Chorin, F., Guérin, O., & Colson, S. S. (2021). Altered Position Sense after Submaximal Eccentric Exercise—inducing Central Fatigue. *Med Sci Sports Exerc*, 53(1), 218-227. <https://doi.org/10.1249/MSS.0000000000002444>
- Da Silva, F., Piponnier, E., Corcelle, B., Blain, G. M., Gioda, J., Colson, S. S., & Monjo, F. (2023). Submaximal fatiguing eccentric contractions of knee flexors alter leg extrapersonal representation. *Heliyon*, 9(8), e18884. <https://doi.org/10.1016/j.heliyon.2023.e18884>
- Docherty, C. L., Moore, J. H., & Arnold, B. L. (1998). Effects of strength training on strength development and joint position sense in functionally unstable ankles. *J. Athl. Train.*, 33(4), 310-314. <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1320579/pdf/jathtrain00012-0016.pdf>
- Dwan, K., Li, T., Altman, D. G., & Elbourne, D. (2019). CONSORT 2010 statement: extension to randomised crossover trials. *bmj*, 366, l4378. <https://doi.org/10.1136/bmj.l4378>
- Fouladi, R., Rajabi, R., Naseri, N., Pourkazemi, F., & Geranmayeh, M. (2012). Menstrual cycle and knee joint position sense in healthy female athletes. *Knee Surgery, Sports Traumatology, Arthroscopy*, 20(8), 1647-1652. <https://doi.org/10.1007/s00167-011-1811-7>
- Gandevia, S. C. (2001). Spinal and supraspinal factors in human muscle fatigue. *Physiol. Rev.*, 81(4), 1725-1789. <https://doi.org/10.1152/physrev.2001.81.4.1725>

- Givoni, N. J., Pham, T., Allen, T. J., & Proske, U. (2007). The effect of quadriceps muscle fatigue on position matching at the knee. *The Journal of physiology*, 584(1), 111-119.
- Gribble, P. A., & Hertel, J. (2004). Effect of lower-extremity muscle fatigue on postural control. *Arch. Phys. Med. Rehabil.*, 85(4), 589-592. <https://doi.org/10.1016/j.apmr.2003.06.031>
- Hermens, H. J., Freriks, B., Disselhorst-Klug, C., & Rau, G. (2000). Development of recommendations for SEMG sensors and sensor placement procedures. *Journal of electromyography and Kinesiology*, 10(5), 361-374. [https://doi.org/https://doi.org/10.1016/S1050-6411\(00\)00027-4](https://doi.org/https://doi.org/10.1016/S1050-6411(00)00027-4)
- IPAQ Research Committee. (2005). Guidelines for data processing and analysis of the International Physical Activity Questionnaire (IPAQ)-short and long forms. https://www.physio-pedia.com/images/c/c7/Quidelines_for_interpreting_the_IPAQ.pdf
- Johannsen, H., Lind, T., Jakobsen, B., & Krøner, K. (1989). Exercise-induced knee joint laxity in distance runners. *Br. J. Sports Med.*, 23(3), 165-168. <https://doi.org/10.1136/bjism.23.3.165>
- Kim, S., Glaviano, N. R., & Park, J. (2023). Exercise-induced fatigue affects knee proprioceptive acuity and quadriceps neuromuscular function more in patients with ACL reconstruction or meniscus surgery than in healthy individuals. *Knee Surg Sports Traumatol Arthrosc*, 31(12), 5428-5437. <https://doi.org/10.1007/s00167-023-07596-5>
- Kröger, S., & Watkins, B. (2021). Muscle spindle function in healthy and diseased muscle. *Skeletal Muscle*, 11, 3. <https://doi.org/10.1186/s13395-020-00258-x>
- LaStayo, P. C., Woolf, J. M., Lewek, M. D., Snyder-Mackler, L., Reich, T., & Lindstedt, S. L. (2003). Eccentric muscle contractions: their contribution to injury, prevention, rehabilitation, and sport. *Journal of Orthopaedic & Sports Physical Therapy*, 33(10), 557-571. <https://doi.org/10.2519/jospt.2003.33.10.557>

- Lephart, S. M., Pincivero, D. M., & Rozzi, S. L. (1998). Proprioception of the ankle and knee. *Sports medicine*, 25(3), 149-155. [https://doi.org/0112-1642/98/0003-0149/\\$03.50/0](https://doi.org/0112-1642/98/0003-0149/$03.50/0)
- Lewek, M., Rudolph, K., Axe, M., & Snyder-Mackler, L. (2002). The effect of insufficient quadriceps strength on gait after anterior cruciate ligament reconstruction. *Clinical biomechanics*, 17(1), 56-63. [https://doi.org/10.1016/S0268-0033\(01\)00097-3](https://doi.org/10.1016/S0268-0033(01)00097-3)
- Lievens, E., Klass, M., Bex, T., & Derave, W. (2020). Muscle fiber typology substantially influences time to recover from high-intensity exercise. *Journal of Applied Physiology*, 128(3), 648-659. <https://doi.org/10.1152/jappphysiol.00636.2019>
- Macgregor, L. J., & Hunter, A. M. (2018). High-threshold motor unit firing reflects force recovery following a bout of damaging eccentric exercise. *PloS one*, 13(4), e0195051. <https://doi.org/10.1371/journal.pone.0195051>
- Maqsood, M., & Váczi, M. (2023). Immediate Effects of Quadriceps Muscle Kinesiology Taping on Joint Position Sense and Force Sense in Healthy Individuals. *Orthopedics and Sports Medicine*. <https://doi.org/10.20944/preprints202303.0188.v1>
- Mathiassen, S. E. (1989). Influence of angular velocity and movement frequency on development of fatigue in repeated isokinetic knee extensions. *European journal of applied physiology and occupational physiology*, 59, 80-88. <https://doi.org/10.1007/BF02396584>
- Michaut, A., Pousson, M., Millet, G., Belleville, J., & Van Hoecke, J. (2003). Maximal voluntary eccentric, isometric and concentric torque recovery following a concentric isokinetic exercise. *International journal of sports medicine*, 24(1), 51-56. <https://doi.org/10.1055/s-2003-37199>
- Nagai, T., Schilaty, N. D., Strauss, J. D., Crowley, E. M., & Hewett, T. E. (2018). Analysis of Lower Extremity Proprioception for Anterior Cruciate Ligament Injury Prevention: Current Opinion. *Sports medicine*, 48(6), 1303-1309. <https://doi.org/10.1007/s40279-018-0889-1>

- Olsson, L., Lund, H., Henriksen, M., Rogind, H., Bliddal, H., & Danneskiold-Samsøe, B. (2004). Test–retest reliability of a knee joint position sense measurement method in sitting and prone position. *Adv. Physiother.*, 6(1), 37-47. <https://doi.org/10.1080/14038190310009894>
- Paschalis, V., Nikolaidis, M. G., Giakas, G., Jamurtas, A. Z., Pappas, A., & Koutedakis, Y. (2007). The effect of eccentric exercise on position sense and joint reaction angle of the lower limbs. *Muscle & nerve*, 35(4), 496-503. <https://doi.org/10.1002/mus.20723>
- Paschalis, V., Nikolaidis, M. G., Theodorou, A. A., Giakas, G., Jamurtas, A. Z., & Koutedakis, Y. (2010). Eccentric exercise affects the upper limbs more than the lower limbs in position sense and reaction angle. *Journal of sports sciences*, 28(1), 33-43. <https://doi.org/10.1080/02640410903334764>
- Pedersen, J., Ljubisavljevic, M., Bergenheim, M., & Johansson, H. (1998). Alterations in information transmission in ensembles of primary muscle spindle afferents after muscle fatigue in heteronymous muscle. *Neurosci.*, 84(3), 953-959. [https://doi.org/10.1016/S0306-4522\(97\)00403-X](https://doi.org/10.1016/S0306-4522(97)00403-X)
- Pickard, C. M., Sullivan, P. E., Allison, G. T., & Singer, K. P. (2003). Is there a difference in hip joint position sense between young and older groups? *J Gerontol A Biol Sci Med Sci.*, 58(7), 631-635. <https://doi.org/10.1093/gerona/58.7.M631>
- Proske, U. (2023). A reassessment of the role of joint receptors in human position sense. *Exp. Brain Res.*, 241(4), 943-949. <https://doi.org/10.1007/s00221-023-06582-0>
- Rampichini, S., Vieira, T. M., Castiglioni, P., & Merati, G. (2020). Complexity analysis of surface electromyography for assessing the myoelectric manifestation of muscle fatigue: A review. *Entropy*, 22(5), 529. <https://doi.org/10.3390/e22050529>
- Ribeiro, F., Venâncio, J., Quintas, P., & Oliveira, J. (2011). The effect of fatigue on knee position sense is not dependent upon the muscle group fatigued. *Muscle and Nerve*, 44(2), 217-220. <https://doi.org/10.1002/mus.22018>

- Riemann, B. L., Myers, J. B., & Lephart, S. M. (2002). Sensorimotor system measurement techniques. *J. Athl. Train.*, 37(1), 85-98. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC164313/pdf/attr_37_01_0085.pdf
- Salgado, E., Ribeiro, F., & Oliveira, J. (2015). Joint-position sense is altered by football pre-participation warm-up exercise and match induced fatigue. *The Knee*, 22(3), 243-248. <https://doi.org/10.1016/j.knee.2014.10.002>
- Sangnier, S., & Tourny-Chollet, C. (2007). Comparison of the decrease in strength between hamstrings and quadriceps during isokinetic fatigue testing in semiprofessional soccer players. *International journal of sports medicine*, 28(11), 952-957. <https://doi.org/10.3233/IES-2003-0121>
- Sealed Envelope Ltd. (2024). *Create a blocked randomisation list*. Retrieved 24 Mar 2025 from <https://www.sealedenvelope.com/simple-randomiser/v1/lists>
- Shokri, P., Eslamian, F., Shakouri, S. K., Ohanian, S., & Jahanjoo, F. (2018). Fatigue Induced Effects after Concentric versus Eccentric Exercises on Sense of Force and Senses of Position among Young Normal Adults-A Controlled Single-Blinded Study. *J. res. med. dent. sci.*, 6(3), 258-267. <https://doi.org/10.24896/jrmds.20186340>
- Steiner, M., Grana, W., Chillag, K., & Schelberg-Karnes, E. (1986). The effect of exercise on anterior-posterior knee laxity. *Am J Sports Med*, 14(1), 24-29. <https://doi.org/10.1177/036354658601400105>
- Tornero-Aguilera, J. F., Jimenez-Morcillo, J., Rubio-Zarapuz, A., & Clemente-Suárez, V. J. (2022). Central and peripheral fatigue in physical exercise explained: A narrative review. *International Journal of Environmental Research and Public Health*, 19(7), 3909. <https://doi.org/10.3390/ijerph19073909>
- Torres, R., Vasques, J., Duarte, J. A., & Cabri, J. M. H. (2010). Knee proprioception after exercise-induced muscle damage. *International*

journal of sports medicine, 31(6), 410-415. <https://doi.org/10.1055/s-0030-1248285>

Vila-Chã, C., Riis, S., Lund, D., Moller, A., Farina, D., & Falla, D. (2011). Effect of unaccustomed eccentric exercise on proprioception of the knee in weight and non-weight bearing tasks. *Journal of electromyography and Kinesiology*, 21(1), 141-147. <https://doi.org/10.1016/j.jelekin.2010.10.001>

Voight, M. L., Hardin, J. A., Blackburn, T. A., Tippet, S., & Canner, G. C. (1996). The effects of muscle fatigue on and the relationship of arm dominance to shoulder proprioception. *J. Orthop. Sports Phys. Ther.*, 23(6), 348-352. <https://doi.org/10.2519/jospt.1996.23.6.348>

Chapter 5

Muscle coactivation during knee joint-position sense assessments: the effect of muscle fatigue and implications for the magnitude of errors and directional bias

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Abstract

Background: Muscle coactivation between knee extensors and flexors has not been described during knee joint-position sense (KJPS) assessments, and its role in the magnitude of errors and directional bias remains unknown. This study aimed to describe muscle coactivation during KJPS assessments in healthy individuals, before and after muscle fatigue, and to analyse the implications for the magnitude of errors and directional bias.

Methods: The KJPS of 21 healthy males was assessed in the sitting position through concentric (SIT_CC) and eccentric repositionings (SIT_ECC) to 45° of knee flexion. Two fatigue protocols were tested, consisting of concentric contractions of the knee extensors or flexors. Muscle coactivation indices were calculated based on the normalized mean activation of the vastus lateralis and biceps femoris muscles. Absolute and relative errors were calculated to group participants by magnitude of errors (lower vs. higher errors) and directional bias (extension vs. flexion).

Results: Coactivation indices ranged between 83.34-98.43% in the SIT_CC and between 74.92-91.41% in the SIT_ECC test. A significant overall decrease in coactivation indices was observed after both fatigue protocols in both KJPS tests ($p < 0.05$). This reduction was mainly due to increased mean EMG activation of the *vastus lateralis*, and decreased activation of the *biceps femoris*, regardless of the fatigued muscle group. No significant differences in coactivation indices were found between magnitude of errors groups ($p > 0.05$), but significantly higher coactivation indices were observed in participants failing the target position into flexion, although only in the SIT_CC test ($0.001 < p < 0.042$).

Conclusion: Muscle coactivation between knee extensors and flexors is high in JPS tests assessed in the sitting position, and decreased after fatigue. Muscle coactivation does not appear to explain the magnitude of errors, while it seems to influence directional bias.

Keywords: muscle coactivation; muscle fatigue; knee; joint-position sense; proprioception; EMG

Introduction

Muscle coactivation is defined as the simultaneous activation of agonist and antagonist muscle groups during voluntary contractions (Psek & Cafarelli, 1993). This motor control mechanism is essential for assisting ligaments in maintaining joint stability and stiffness during functional activities, as well as ensuring an even distribution of joint loading (Baratta et al., 1988; Smith et al., 2019).

Particularly in the knee, coactivation of the hamstrings during quadriceps contractions enhances knee stability by limiting anterior tibial translation, thereby reducing the tensile load on the anterior cruciate ligament (Yanagawa et al., 2002). However, high levels of coactivation may also contribute to degenerative changes, as they can increase joint contact pressures and interfere with normal load distribution (Mills et al., 2013; Sharma et al., 2017).

Joint-position sense (JPS) is assessed by the ability to accurately reproduce a previously demonstrated joint angle, consisting of a proprioceptive ability that enables the recognition of a body segment's position in space (Riemann et al., 2002). This sense relies on the input to the central nervous system (CNS) from different mechanoreceptors located in the skin, joints, and muscle structures, whose integrity is essential for generating appropriate motor responses, necessary to ensure joint stability (Lephart et al., 1998; Nagai et al., 2018). In this context, the muscle spindle is a muscle mechanoreceptor described as the primary source of proprioceptive input, signalling changes in muscle length and similarly controlling muscle stretch (Proske, 2023; Riemann et al., 2002; Voight et al., 1996). However, muscle fatigue has been argued to cause an increase in the discharge threshold of the muscle spindle (Balestra et al., 1992; Pedersen et al., 1998), potentially affecting the proprioceptive input to the CNS and impairing the ability to quickly respond to joint disturbances.

Muscle coactivation of the knee extensors and flexors has been described during isometric (Wu et al., 2017) and concentric/eccentric contractions (Alkjær et al., 2012). However, although it has been suggested that coactivation of agonists and antagonists may enhance movement accuracy (Gribble et al., 2003), the specific contributions of these muscles and their coactivation indices during JPS

assessments have not been investigated, either in fatigued and non-fatigued conditions. Likewise, it remains unknown whether, and how, these contributions and coactivation patterns change following the induction of muscle fatigue, either in the agonist or antagonist muscles.

Knee JPS tests can be performed under weight-bearing (in closed kinetic chain) or non-weight-bearing conditions (open kinetic chain). Although previous studies suggest that weight-bearing tests yield greater accuracy (Andersen et al., 1995; Herrington, 2005), they have the disadvantage that the repositioning depends on the cumulative contributions of multiple joints and their associated muscles of the lower limb (Andersen et al., 1995). This makes it impossible to isolate and assess the proprioceptive acuity of a single joint, which can only be achieved in non-weight-bearing tests (Stillman & McMeeken, 2001). Accordingly, among the possible positions for assessing knee JPS under non-weight-bearing conditions, the sitting position is the most widely used, showing fewer repositioning errors than other test positions, such as the prone position. Furthermore, it offers higher reliability and greater reported comfort (Olsson et al., 2004).

Additionally, JPS can be estimated by calculating different repositioning errors. While absolute angular errors indicate the magnitude of the errors, the relative angular errors reveal directional bias (Vila-Chã et al., 2023), helping to determine whether the target position was failed in the direction of greater flexion or extension than intended. To the best of the authors' knowledge, it has not yet been investigated whether possible differences in muscle coactivation exist between individuals with lower and higher errors, and between those who fail the target position in the direction of flexion or extension. Understanding these differences may help explain the commonly observed variability in the magnitude of errors or directional bias among individuals without a history of knee injuries.

In that sense, the primary aim of this study was to describe the muscle coactivation of the knee extensors and flexors during knee JPS assessments, both before and after inducing two different muscle fatigue protocols in healthy individuals. As a secondary aim, differences in the muscle coactivation will be analysed between those with lower and higher magnitudes of repositioning

errors, and between those who fail the target positions by describing more flexion or extension. The authors hypothesize that muscle coactivation indices will be high, as JPS requires high movement accuracy. Also, since fatiguing exercise has been linked to joint instability at the knee joint (Melnyk & Gollhofer, 2007), a decrease in muscle coactivation is expected after fatigue. Likewise, muscle coactivation is likely to differ between individuals with lower and higher errors, and between those failing the target positions in the direction of flexion or extension. Finally, since previous studies have shown sex differences in muscle coactivation, with females presenting higher muscle coactivation, attributed as a possible mechanism to compensate for the lower muscle strength, only male participants were included (Smith et al., 2021; Smith et al., 2020).

Methods

Study Design and Participants

This quasi-experimental study was reported following the TREND Statement Checklist (Des Jarlais et al., 2004; Haynes et al., 2021). The calculation of the necessary sample size to achieve 95% power, with $\alpha = 5\%$ to detect differences in the outcomes between assessments was performed indicating that 16 participants were required. Considering potential dropouts, a convenience sample of 22 healthy males was recruited.

Individuals were eligible if they were males aged between 18 and 30 years, and had no current or previous knee pathology or had been submitted to a knee surgery. Excluded were those with: cardiorespiratory conditions that could prevent the execution of fatiguing exercise; neurological or vestibular disorders potentially affecting JPS; knee joint integrity tests suggesting instability; and using medication with an effect on motor control (sedatives, anxiolytics, antibiotics, analgesics, anti-inflammatories, or myorelaxants). Furthermore, indications to avoid fatiguing activities and alcohol in the 48 hours before each session were also given. Participants self-reported their medical history, and an experienced

physical therapist (J.A.) assessed the knee joint integrity tests (anterior and posterior drawer, Lachman's test, valgus and varus stress tests).

Data were collected between November 2023 and May 2024, at the Porto Biomechanics Laboratory – University of Porto, Portugal. Participants reported to the laboratory on two sessions, separated by at least two weeks (Shokri et al., 2018), to perform two different muscle fatigue protocols, whose order was randomised. The first protocol was defined by block randomization and generated on an online platform (Sealed Envelope Ltd, 2024).

The Ethics Committee of the Faculty of Sport, University of Porto approved the study. All participants provided written informed consent to participate in the study, and all procedures were conducted following the Declaration of Helsinki.

Knee Joint-Position Sense Assessments

Knee JPS assessments were conducted using an isokinetic dynamometer (Biodex Medical Systems 4, Biodex, Shirley, New York, USA), which was previously demonstrated to be a valid and reliable tool to assess knee joint position (Drouin et al., 2004). Assessments were performed in a silent environment to avoid potential sources of bias, and participants wore a blindfold to eliminate visual input. All assessments were performed on the dominant limb, which was indicated as the preferred lower limb to kick a ball, following an ipsilateral repositioning to the target angle of 45° of knee flexion (Azevedo, Rodrigues, et al., 2024).

Two JPS tests in the sitting position were executed randomly, involving a concentric and an eccentric repositioning (Clark et al., 2016). In the concentric repositioning (SIT_CC), a starting position of 90° of knee flexion was adopted, from which the participant had to perform a concentric extension until the 45° angle was reached (Figure 1). For the eccentric repositioning (SIT_ECC), the leg began in full knee extension, and an eccentric flexion was performed until the target angle was reached (Figure 2). In both tests, participants actively moved their leg until the dynamometer lever blocked, maintaining the target position for

five seconds to allow memorization. Then, they returned to the starting position and actively attempted to reproduce the target angle.

Each participant performed three repositioning attempts. Angles were recorded when the participant verbally confirmed having reached the position, and the average of the three attempts was used. Knee JPS was estimated by calculating absolute (AAE) and relative (RAE) angular errors, representing the absolute and arithmetic difference, respectively, between the target and reproduced angles (Bennell et al., 2005).

These JPS tests were performed before and immediately after the muscle fatigue protocols. The same assessor (J.A.) administered all procedures.



Figure 1. JPS procedures for the SIT_CC test: (A) describes the starting position (90° of knee flexion), and (B) the leg positioned at the target angle (45° of knee flexion).



Figure 2. JPS procedures for the SIT_ECC test: (A) describes the starting position (full knee extension), and (B) the leg positioned at the target angle (45° of knee flexion).

Muscle Fatigue Protocols

Participants first underwent maximal voluntary isometric contraction (MVIC) testing for the quadriceps and hamstrings at 60° of knee flexion (Da Silva et al., 2022).

Two muscle fatigue protocols targeting the knee extensors (quadriceps) and flexors (hamstrings) of the dominant limb were performed:

- i) The quadriceps fatigue protocol (QD_CC), which involved 40 consecutive maximal concentric contractions at 30°/s, between 90° and 30° knee flexion;
- ii) The hamstring fatigue protocol (HS_CC), which consisted of 30 consecutive maximal concentric contractions at 30°/s, between 30° and 90° knee flexion.

The MVIC and muscle fatigue protocols were performed in the isokinetic dynamometer. Verbal encouragement and visual feedback from the dynamometer screen were provided to elicit the participants to give their maximum effort.

Electromyography

EMG data were recorded during the knee JPS assessments, MVIC, and fatigue protocols procedures, using two sEMG Galileo sensors (Delsys, Natick, USA). The sensory head of these sensors was placed on the vastus lateralis and biceps femoris, as representatives of the knee extensors and flexors, respectively (Aragão et al., 2015; Baroni et al., 2013). Before sensors' placement, the skin was prepared, shaved, abraded, and cleaned with alcohol. Sensors were then placed on dry skin over the belly of the referred muscles in the direction of the muscle fibres, following the SENIAM recommendations (Hermens et al., 2000). The sensor's heads were placed at a 2/3 distance from the anterosuperior iliac spine and the lateral side of the patella, considering the vastus lateralis muscle; and at a middle distance between the ischial tuberosity and the lateral epicondyle

of the tibia for the biceps femoris muscle. The main body of the two sensors was positioned parallel to the respective sensor's head. An additional Delsys Analog Sensor (Delsys Inc., Boston, MA, USA) was used to synchronously collect data from the isokinetic dynamometer, namely, angular position and torque. Data were acquired using the Delsys EMGWorks 4.8.0 software (Delsys Inc., Boston, MA, USA), at a sampling frequency of 2222 Hz (EMG) and 518 Hz (dynamometric data). To analyse the presence of excessive baseline noise, an initial inspection of the EMG channels was conducted to check if the 10 μ V baseline noise was not exceeded (Macgregor & Hunter, 2018).

Data Processing

A custom script was written in MATLAB R2024b (Mathworks, Natick, MA, USA) to process EMG and dynamometric data.

A single channel from each Galileo sensor was selected for further analysis. EMG signals were band-pass filtered (20–450 Hz) using a second-order bidirectional Butterworth filter, full-wave rectified, and the Root Mean Square (RMS) envelopes were calculated using a 100-ms window. EMG data were normalized to the maximum activation of the corresponding muscle MVIC. Angular position was low-pass filtered using a second-order bidirectional Butterworth filter at 6 Hz, and torque data were low-pass filtered at 100 Hz.

To verify the presence of muscle fatigue, the initial and final contractions of each muscle fatigue protocol were excluded, and the analysis was performed on the first and last three contractions, which were individually analysed. Regarding the retrieved variables, for torque, the mean and peak torque were obtained, whereas for EMG variables, the mean and peak activation, as well as the median frequency, were extracted.

For the JPS tests, based on angular position, two distinct periods were segmented for EMG analysis:

i) the concentric (SIT_CC) or eccentric (SIT_ECC) repositioning phase from the starting position to the target position (RPOS);

ii) the five-second isometric contraction while holding the target position between repositioning attempts (STABLE).

The average of the three repositioning attempts was used for both periods, and the mean activations of the vastus lateralis and biceps femoris were retrieved.

Muscle Coactivation

Muscle coactivation was calculated by a coactivation index (CI) based on normalized mean EMG activation of agonist and antagonist muscles during the knee JPS assessments, and expressed as a percentage (%) (Ervilha et al., 2012):

$$CI = 2 \times \frac{\text{EMG antagonist}}{(\text{EMG Agonist} + \text{EMG Antagonist})} \times 100 \quad (1)$$

In both JPS tests, the knee extensors (i.e., *vastus lateralis*) were considered the agonists, and the knee flexors (i.e., *biceps femoris*) were considered the antagonists.

Statistical Analysis

Statistical analysis was performed using IBM SPSS v.27 for Windows, considering a significance level of 0.05.

Normality of variable distribution was tested using the Shapiro-Wilk test, which was not confirmed. Therefore, quantitative variables (age, body mass, height, body mass index, body fat, mean and peak torque, mean and peak activation, median frequency, AAE, muscle coactivation index, and mean EMG activations) were reported as Median (Interquartile Range). Categorical variables (dominance) were described as frequency (n) and percentage (%).

To assess the implications of muscle coactivation on the magnitude of errors, participants were divided into two groups based on the median AAE values from the SIT_CC and SIT_ECC JPS tests: those with lower errors and those with higher errors. To assess the implications on the directional bias, participants were also grouped according to RAE values: those who failed the target angle by describing more knee extension than supposed (indicated by positive values in the calculation of RAE), or by describing more flexion than supposed (indicated by negative values in the calculation of RAE).

Non-parametric Wilcoxon and Mann-Whitney tests were used. The Wilcoxon test assessed within-group changes in: i) torque and EMG variables between the initial and final contractions of the muscle fatigue protocols; and ii) coactivation indices and mean EMG activations of the vastus lateralis and biceps femoris between pre- and post-fatigue JPS assessments. The Mann-Whitney test was used for intergroup comparisons: i) to verify the existence of differences in the muscle coactivation indexes between muscle fatigue protocols (HS_CC and QD_CC); and ii) to check for differences in the muscle coactivation index and mean activation of the vastus lateralis and biceps femoris between magnitude of errors' groups and between directional bias's groups.

For statistically significant results, the effect size (r) was calculated by dividing the Z statistic by the square root of the number of observations ($r = Z/\sqrt{N}$) (Rosenthal, 1991). Effect size was interpreted as small ($r=0.10$), medium ($r=0.30$), and large ($r=0.50$) (Cohen, 1988).

Results

From the initial 22 participants, 21 completed all study procedures (4.5% drop-out rate). Participants had an age of 23 (5) years, a body mass of 72.2 (9.4) kg, a height of 1.76 (0.12) m, and a BMI of 24.3 (2.0) kg/m². The right lower limb was the dominant one in 17 participants (81.0%), and the left in 4 participants (19.0%).

Table 1 presents the torque and EMG results between the initial and final group of three contractions of the fatigue protocols, evidencing the development of

fatigue after both protocols to which the participants were submitted (QD_CC and HS_CC). Effectively, both fatigue protocols produced a significant decrease in mean and peak torque between the initial and final contractions. Specifically analysing peak torque, the QD_CC protocol caused a significant decrease of 21.0% ($p = 0.004$; $r = 0.63$), and the HS_CC protocol, a significant decrease of 25.1% ($p < 0.001$; $r = 0.74$). Regarding mean and peak EMG, no significant changes were observed between the beginning and the end of both protocols ($p > 0.05$). However, the median frequency significantly decreased at the end of both QD_CC ($p < 0.001$; $r = 0.73$). and HS_CC ($p < 0.001$; $r = 0.87$) protocols.

Table 1: Torque and EMG results between the initial (Beg.) and final (End) contractions of the muscle fatigue protocols.

Variable	Period	QD_CC	HS_CC
Mean Torque (N.m)	Beg. ^a	133.1 (44.7)	92.1 (37.0)
	End ^a	86.9 (26.2)	62.4 (14.6)
	p^b	<0.001*	<0.001*
Peak Torque (N.m)	Beg. ^a	171.1 (38.2)	111.1 (40.3)
	End ^a	135.2 (45.1)	83.2 (24.8)
	p^b	0.004*	<0.001*
Mean EMG (%MVIC)	Beg. ^a	44.5 (23.7)	42.7 (20.4)
	End ^a	44.8 (26.4)	36.5 (24.3)
	p^b	0.566	0.068
Peak EMG (%MVIC)	Beg. ^a	88.9 (40.4)	88.5 (39.0)
	End ^a	85.1 (51.1)	85.6 (58.9)
	p^b	0.455	0.455
Median Frequency (Hz)	Beg. ^a	63.2 (7.9)	74.4 (18.4)
	End ^a	58.1 (5.8)	62.1 (18.3)
	p^b	<0.001*	<0.001*

Notes: Beg.: 3 first contractions of the protocol; End: 3 last contractions of the protocol; QD_CC: quadriceps concentric fatigue protocol; HS_CC: hamstrings concentric fatigue protocol; ^a Median (Interquartile Range); ^b Wilcoxon Test; * $p < 0.05$

Muscle coactivation before and after inducing muscle fatigue

Figure 3 shows the coactivation results before and after inducing muscle fatigue (PRE vs. POST) for the quadriceps (QD_CC) and hamstrings (HS_CC). Pre-fatigue coactivation results show high coactivation indices, with the medians ranging between 83.34% and 98.43% in the SIT_CC test, and between 74.92% and 91.41% in the SIT_ECC test, indicating close mean EMG activations between the agonist (*vastus lateralis*) and antagonist (*biceps femoris*) muscles involved in the JPS motions.

Overall, a decrease in coactivation indices was observed with fatigue. However, in the SIT_CC test, significant reductions were only found after the hamstrings fatigue protocol in the RPOS period ($p = 0.002$; $r = 0.47$), and after the quadriceps fatigue protocol in the STABLE period ($p = 0.042$; $r = 0.31$). In the SIT_ECC test, a significant decrease was also observed after the hamstrings fatigue protocol in the RPOS period ($p = 0.023$; $r = 0.35$) and after the quadriceps fatigue protocol in the STABLE period ($p = 0.039$; $r = 0.32$). In general, higher coactivation indices were observed after the quadriceps fatigue protocol, although a significant difference was only confirmed in the RPOS period of the SIT_CC test ($p = 0.023$; $r = 0.35$).

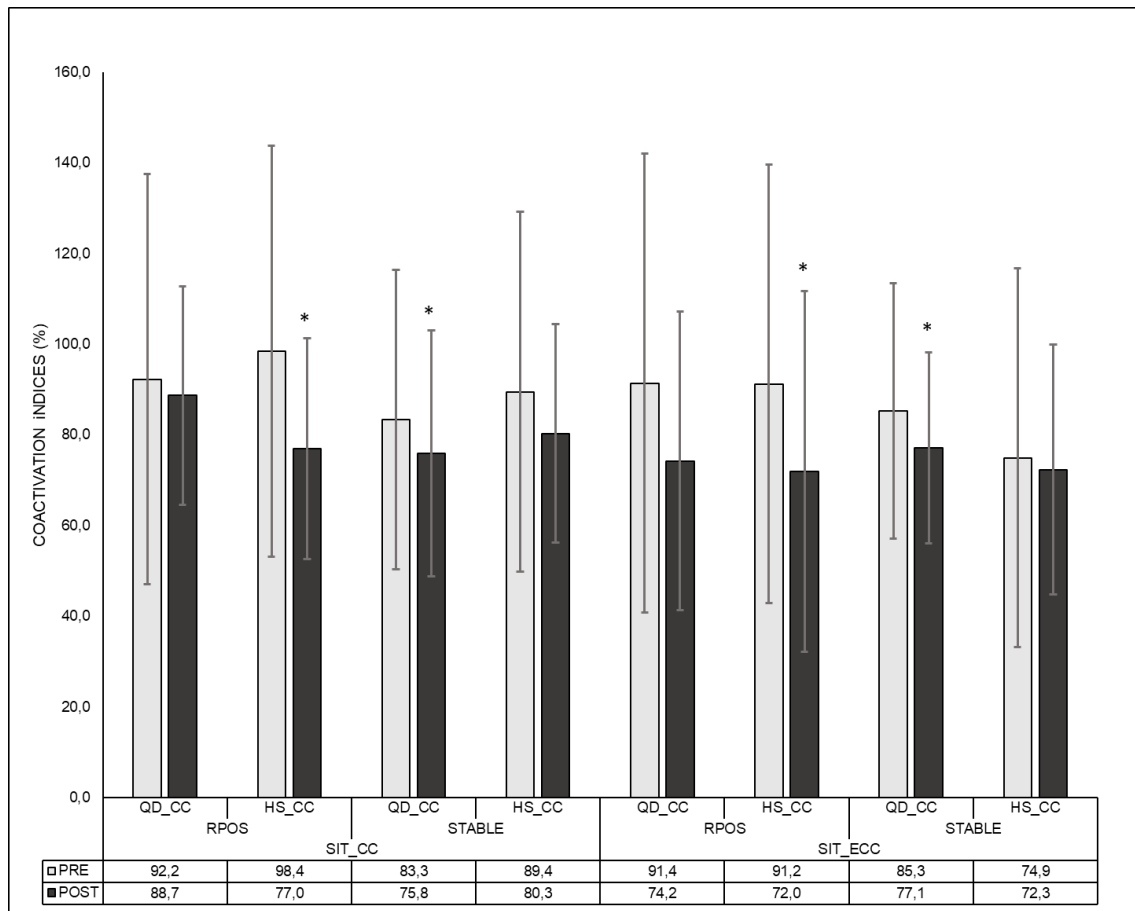


Figure 3. Coactivation results in the assessed JPS tests, before (PRE) and after (POST) inducing fatigue on the quadriceps (QD_CC) and hamstrings (HS_CC); RPOS: repositioning period from the starting position to the target position; STABLE: period of isometric contraction while holding the target position between repositioning attempts; * *significantly different from PRE*.

Figure 4 describes the mean EMG activations for the *vastus lateralis* and *biceps femoris* during the assessed JPS tests, before and after muscle fatigue (PRE vs. POST) of the quadriceps (QD_CC) and hamstrings (HS_CC). Overall, the observed decrease in the coactivation indices after fatigue appeared to be primarily due to an increase in the mean activation of the agonist muscle (*vastus lateralis*), accompanied by a decrease in the mean activation of the antagonist (*biceps femoris*). Effectively, regarding the *biceps femoris*, PRE vs. POST comparisons for the hamstrings fatigue protocol revealed significant reductions in both JPS tests and both analysed periods ($0.001 < p < 0.002$; $0.69 < r < 0.79$). Following the quadriceps fatigue protocol, the *biceps femoris* also showed significant reductions in its mean EMG activation from PRE to POST

($0.008 < p < 0.030$; $0.47 < r < 0.58$), except in the RPOS period of the SIT_CC test ($p = 0.205$). Regarding the *vastus lateralis*, a significant increase POST fatigue was observed in the RPOS period of the SIT_CC test, both in the quadriceps ($p = 0.005$; $r = 0.43$) and hamstrings ($p = 0.038$; $r = 0.32$) fatigue protocols.

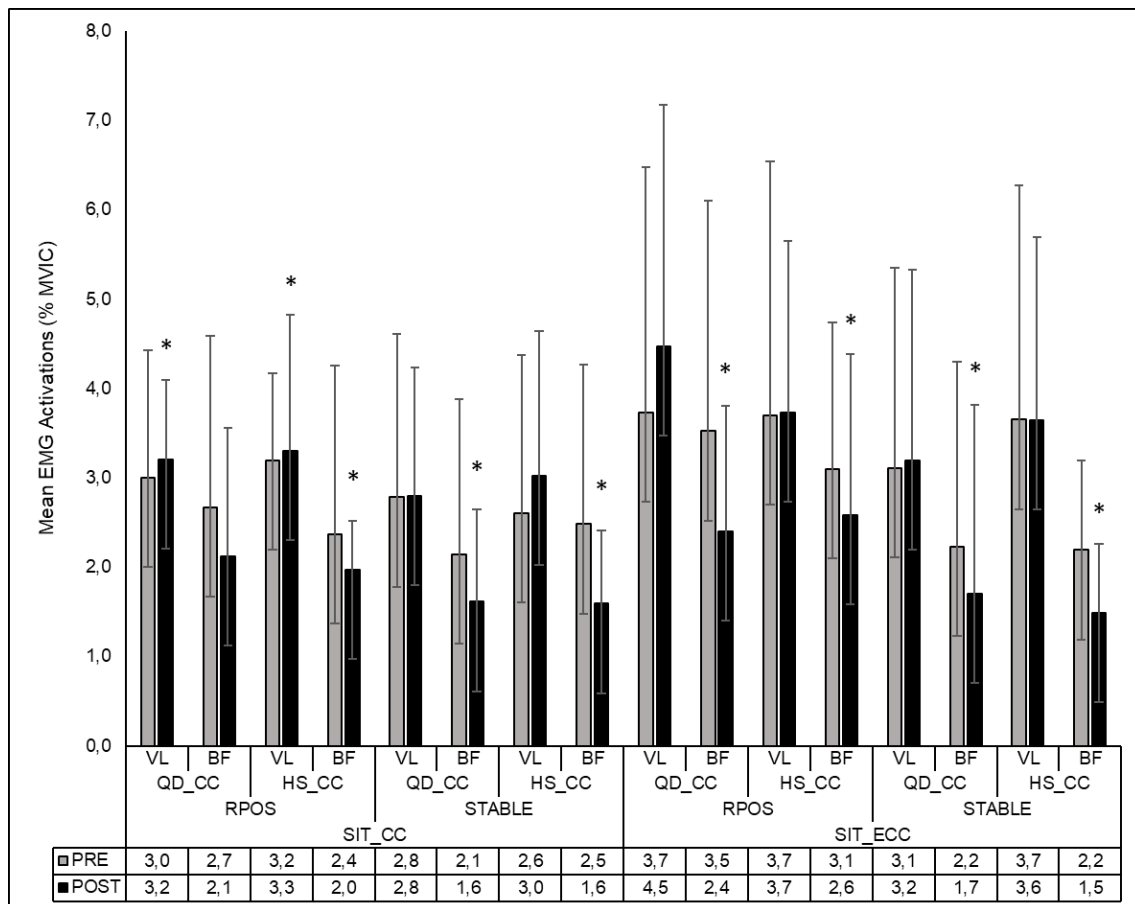


Figure 4. Vastus lateralis (VL) and biceps femoris (BF) mean EMG activation results in the assessed JPS tests, before (PRE) and after (POST) inducing fatigue on the quadriceps (QD_CC) and hamstrings (HS_CC); MVIC: Maximum Voluntary Isometric Contraction; SIT_CC: concentric repositioning test; SIT_ECC: eccentric repositioning test; RPOS: repositioning period from the starting position to the target position; STABLE: period of isometric contraction while holding the target position between repositioning attempts; * *significantly different from PRE*.

Implications of muscle coactivation for the magnitude of errors and directional bias

The pre-fatigue median of AAE was 3.0° (3.8) in the SIT_CC test, and 3.3° (4.3) in the SIT_ECC. These baseline values were used to create the groups of errors' magnitude (lower errors vs. higher errors).

For the directional bias analysis, participants were grouped based on whether they failed to reach the target angle in the direction of flexion or extension. In the SIT_CC test, 61.9% of the participants failed in the direction of extension, whereas in the SIT_ECC test, 76.2% failed in the direction of flexion.

Table 2 describes the comparison of the coactivation indices and mean EMG activations of the *vastus lateralis* and *biceps femoris* between the groups of magnitude of errors and groups of directional bias.

Concerning the magnitude of errors, no significant differences were observed in either the SIT_CC or SIT_ECC JPS tests between participants with lower and higher errors in the coactivation indices, or in mean EMG activation of the *vastus lateralis* and *biceps femoris* ($p > 0.05$).

Regarding directional bias, significant differences were found only for the SIT_CC test. Participants who failed the target angle by describing more extension presented significantly lower coactivation indices in the RPOS ($p = 0.042$; $r = 0.29$) and STABLE ($p = 0.001$; $r = 0.49$) periods, significantly higher mean EMG activation of the *vastus lateralis* in both RPOS ($p = 0.007$; $r = 0.42$) and STABLE ($p < 0.001$; $r = 0.52$) periods, and significantly lower mean EMG activation of the *biceps femoris* only in the RPOS period ($p = 0.001$; $r = 0.60$).

Table 2. Comparisons of coactivations and mean activations of VL and BF between the participants presenting lower and more errors (magnitude of errors comparison) and those failing the target angle into the extension or flexion direction (directional bias), before and after fatigue.

JPS test	Variable	Period	Magnitude of Errors			Directional Bias		
			Lower errors	Higher errors	<i>p</i>	Extension	Flexion	<i>p</i>
SIT_CC	COACTIVATION (%)	RPOS	72.9 (19.1)	82.9 (37.2)	0.199	72.3 (34.3)	76.6 (35.5)	72.9 (19.1)
		STABLE	78.4 (59.0)	81.7 (26.8)	0.414	67.5 (49.7)	87.4 (35.8)	78.4 (59.0)
	MEAN VL (%MVIC)	RPOS	3.2 (1.7)	3.0 (1.0)	0.375	3.1 (0.8)	2.8 (1.3)	3.2 (1.7)
		STABLE	2.8 (2.2)	2.6 (1.6)	0.990	3.6 (2.6)	2.6 (1.5)	2.8 (2.2)
	MEAN BF (%MVIC)	RPOS	2.2 (1.9)	2.6 (1.7)	0.546	2.1 (1.1)	2.7 (2.5)	2.2 (1.9)
		STABLE	1.8 (1.6)	2.5 (1.6)	0.191	2.1 (1.1)	2.5 (2.1)	1.8 (1.6)
SIT_ECC	COACTIVATION (%)	RPOS	90.3 (61.9)	93.7 (27.4)	0.687	87.5 (52.1)	90.7 (41.9)	90.3 (61.9)
		STABLE	72.9 (37.1)	85.9 (24.7)	0.724	77.0 (28.1)	76.9 (41.0)	72.9 (37.1)
	MEAN VL (%MVIC)	RPOS	3.8 (3.4)	3.7 (2.1)	0.668	3.7 (3.2)	3.8 (2.0)	3.8 (3.4)
		STABLE	3.3 (3.0)	3.1 (1.6)	0.481	3.1 (1.6)	4.5 (2.9)	3.3 (3.0)
	MEAN BF (%MVIC)	RPOS	3.3 (2.4)	3.2 (1.7)	0.860	3.1 (2.0)	3.3 (3.2)	3.3 (2.4)
		STABLE	2.2 (1.6)	2.2 (1.2)	0.724	2.0 (1.3)	2.5 (1.8)	2.2 (1.6)

Note: Variables described as Median (Interquartile Range); BF: *biceps femoris*; VL: *vastus lateralis*; MVIC: Maximum Voluntary Isometric Contraction; SIT_CC: concentric repositioning test; SIT_ECC: eccentric repositioning test; RPOS: repositioning period from the starting position to the target position; STABLE: period of isometric contraction while holding the target position between repositioning attempts. **p*<0.05

Discussion

The primary aim of this study was to describe the muscle coactivation of the knee extensors and flexors during knee JPS assessments, both before and after inducing two different muscle fatigue protocols in healthy individuals. As a secondary aim, differences in the muscle coactivation were analysed between those with lower and higher magnitudes of repositioning errors, and between those who failed the target positions by describing more flexion or extension.

The two muscle fatigue protocols were conducted at an angular velocity of 30°/s. This velocity has been formerly employed to investigate the acute effects of muscle fatigue on different knee proprioceptive submodalities, where significant deleterious effects were reported (Da Silva et al., 2022; Da Silva et al., 2021). Moreover, it has been shown that muscle fatigue tends to develop more markedly at slower angular velocities, such as 30°/s, compared with higher velocities (Mathiassen, 1989).

Prior evidence indicates that the force decline induced by muscle fatigue differs between the quadriceps and hamstring muscle groups (Sangnier & Tourny-Chollet, 2007). Specifically, force appears to decrease more substantially in the hamstrings than in the quadriceps, which may be attributed to structural differences, particularly in the relative distribution of fast- and slow-twitch muscle fibers (Lievens et al., 2020). On this basis, 40 contractions were adopted for the quadriceps fatigue protocol, whereas 30 contractions were applied to fatigue the hamstrings.

Muscle coactivation before and after inducing muscle fatigue

Confirming the initial hypothesis, the first finding of the present study was that the muscle coactivation indices of the knee extensors and flexors were high in the assessed JPS tests in pre-fatigue assessments. These coactivation indices were slightly higher in the SIT_CC test, with medians of coactivation indices ranging between 83.34% and 98.43%, while in the SIT_ECC test, they ranged between 74.92% and 91.41%. Enoka (1997) proposed that high levels of muscle

coactivation represent a valuable strategy in motions requiring high precision, being therefore an essential mechanism for accurately repositioning a previously demonstrated angle. In addition to motion accuracy, high coactivation levels constitute a necessary mechanism for joint stability, as they lead to increased joint stiffness, diminishing the joint's vulnerability to internal or external disturbances (Kornecki, 1992).

An analysis of the mean EMG activation of the two involved muscles revealed marginally higher activations of the vastus lateralis, the agonist of the performed JPS tasks. However, the biceps femoris also exhibited comparable activation levels, which helps to account for the high coactivation indices observed between them.

The nearly similar mean EMG activations observed between the *vastus lateralis* and *biceps femoris* may be due to the antagonist (*biceps femoris*) needing to decelerate the movement as the participant perceives proximity to the target angle. Additionally, adjustments are often observed when the target angle is reached, as individuals tend to perceive that they have either overestimated or underestimated the intended position and attempt to correct it.

In the SIT_CC test, which involved a concentric extension motion starting from 90° of knee flexion, more than half of the participants (61.9%) failed the target angle by describing more extension. Consequently, to reduce the repositioning error, adjustment strategies towards flexion had to be adopted to more closely approximate the previously demonstrated angle. One such strategy may have involved activating the *biceps femoris* to lower the leg towards what was perceived as the correct position. Conversely, in the SIT_ECC test, which began from full knee extension and involved an eccentric flexion motion towards the target angle, a higher percentage of participants (76.2%) missed the target by exceeding the intended flexion. Therefore, a corrective adjustment toward extension would have been necessary to reduce the error and accurately reach the target position. In theory, this would result in a higher mean activation of the *vastus lateralis*, increasing the difference in the mean activation between the two

muscles in favour of the agonist (*vastus lateralis*). These strategies may explain the slightly lower coactivation indices previously reported for the SIT_ECC test.

This study analysed two periods for mean EMG activation and muscle coactivation. The selected repositioning period comprehended the time elapsed from the starting position to the point at which the participant identified having reached the target angle. This period also included the adjustments made in cases where the target position was either overestimated or underestimated. During this period, since angular position changes, coactivation is expected to be lower at the onset of the repositioning motion to allow for initial acceleration. As the segment approaches the target position, coactivation increases to act as a dynamic brake and to facilitate necessary adjustments (Latash, 2018). To reduce this variability and estimate the mean EMG activation of the two involved muscles at the identified point by the participant as corresponding to the target position, the stability period during which the participant held the position isometrically (before returning to the initial position for the next repositioning attempt) was also analysed.

The second finding of this study was that fatigue led to a decrease in coactivation indices between the knee extensors (quadriceps) and flexors (hamstrings), thereby confirming the initial hypothesis. This decrease was observed in both JPS tests, across both analysed periods, and following both fatigue protocols. Regarding the quadriceps fatigue protocol, the coactivation index in the SIT_CC test reduced 3.8% during the repositioning period and 9.0% during the isometric contraction period (STABLE). In the SIT_ECC test, the decrease was 18.8% and 9.5%, for the same periods, respectively. Following the hamstrings fatigue protocol, the coactivation index in the SIT_CC test decreased by 21.8% during repositioning and 10.3% during the STABLE period, while in the SIT_ECC test, the decrease was 21.0% and 3.44%, respectively.

However, relying exclusively on the coactivation index may not be the most accurate way to interpret the contributions of the involved muscles, particularly under fatigue conditions. In fact, different agonist and antagonist muscle groups' behaviours can influence the coactivation index. Therefore, understanding how

the mean EMG activations of these muscles change between baseline and post-fatigue assessments is essential to clarify the mechanisms behind the observed decrease in coactivation. Analysis of the present data shows that the reduction in coactivation index following fatigue was due to an increase in the mean EMG activation of the agonist muscle (*vastus lateralis*), combined with a decrease in the mean EMG activation of the antagonist (*biceps femoris*). This pattern appeared to be independent of the fatigued muscle group, as the same trend was observed after both fatigue protocols, regardless of whether fatigue was induced in the agonist or antagonist muscle.

The observed reduction in the coactivation indices following muscle fatigue may be explained by neural mechanisms that prioritize task execution over joint stabilization. Specifically, the increase in mean EMG activation of the vastus lateralis suggests enhanced excitability of agonist motor pathways as a compensatory strategy to counteract contractile inefficiency under fatigue conditions (Duchateau & Baudry, 2014). In contrast, the observed decrease of biceps femoris activation may reflect augmented reciprocal inhibition and reduced proprioceptive input from the fatigued muscles, attenuating antagonist recruitment (Aymard et al., 1995). This pattern is consistent with central strategies aiming to conserve energy, since high levels of coactivation impose additional metabolic demands (Latash, 2018). While these neural mechanisms allow the motion to be completed under fatigue, it also compromises active joint stability, thereby increasing load on passive stabilizers, potentially increasing the risk of injury (Baratta et al., 1988). Moreover, the appearance of pain during sustained and fatiguing muscle contractions cannot be disregarded (Mastaglia, 2012). Both pain and muscle fatigue may alter muscle coactivation, although through distinct neurophysiological mechanisms, which still ultimately disrupts the ideal balance between agonist and antagonist muscles, compromising joint stability. As already discussed, while fatigue seems to reduce coactivation by changing motor and reflex strategies, giving preference to task execution rather than stability (Aymard et al., 1995; Duchateau & Baudry, 2014), pain appears to induce an increase in coactivation as a protective strategy to enhance joint stiffness and limit harmful motions. Nevertheless, available evidence to support this suggestion was only

validated in the neck (Lindstrøm et al., 2011) and low-back (Varrecchia et al., 2022).

Although assessing a different proprioceptive subcomponent, Kiyama et al. (2014) conducted a study to understand the effect of muscle fatigue on force sense. Similarly to the present study, the knee extensors were fatigued through concentric contractions, and an increase in EMG activity of this muscle group was observed. However, EMG activity from the hamstrings was not assessed, not allowing comparison with this variable. It is possible that the central nervous system compensates for the peripheral and deleterious effects of muscle fatigue by increasing the number of recruited motor units, thereby resulting in higher EMG activity (Carpentier et al., 2001). While this may be a strategy to preserve joint stability, Kiyama et al. (2014) suggested that increased muscle activity may interfere with the estimation of force output. Given that both force sense and JPS assessed through active tests rely on the same type of mechanoreceptors located in muscles and tendons (Hassanlouei et al., 2012; Riemann & Lephart, 2002), it is plausible that increased EMG activity following fatigue may also interfere with segmental position estimation, due to an overload of sensory information for central processing. In support of this, a recent systematic review confirms the negative impact of different fatigue protocols on the knee JPS, significantly increasing repositioning errors (Azevedo, Moreira-Silva, et al., 2024). Nevertheless, the hypothesis that an increased number of recruited motor units acts as a compensatory mechanism still requires further investigation, ideally using decomposition electromyography, to quantify motor unit recruitment under baseline and post-fatigue conditions.

Concerning the effect of fatigue in the antagonist muscle group (hamstrings), in Melnyk and Gollhofer (2007) study, the participants underwent a fatigue protocol involving concentric and eccentric hamstring contractions. In line with the present findings, a significant reduction in EMG amplitude of the hamstrings was observed post-fatigue. Furthermore, anterior tibial translation was also assessed, with results indicating that fatigue increased this translation, suggesting that hamstrings fatigue is indeed associated with mechanical loss of knee joint stability. The findings by Melnyk and Gollhofer (2007) therefore contribute to

understanding the reasons behind the increased repositioning errors observed after fatigue. Effectively, decreased hamstrings activity implies reduced control over the repositioning motion and diminished capacity to accurately perform the necessary adjustments to reach the target position.

In this context, the present findings, together with those reported by Melnyk & Gollhofer (2007), reinforce the need to design knee injury prevention programs that emphasize neuromuscular strategies, such as proprioceptive and balance exercises, aiming to enhance reflexive responses to both internal and external disturbances, even when muscle fatigue is present. Balanced strengthening of agonist and antagonist muscles is also essential, with particular emphasis on exercises that promote muscle coactivation (Begalle et al., 2012), given that when active stability fails, greater loads are transferred to passive stabilizers, namely the menisci and ligaments. Effectively, low hamstrings:quadriceps force ratios have been related to ACL injuries, as the hamstrings fail to provide resistance to anterior tibial translation, being recommended that this ratio be 0.6 or more to assure the joint stability (Padasala et al., 2020). Moreover, the adjustment of specific technical motions is required, particularly voluntary changes of landing mechanics following jumps, to prevent injurious patterns, such as excessive tibial translation or landings in knee hyperextension (Ortiz et al., 2010). Finally, adequate cardiovascular conditioning, together with exercises that increase muscular endurance, should also be prioritized, as these may contribute to delaying the onset of fatigue.

Implications of muscle coactivation for the magnitude of errors and directional bias

Regarding the magnitude of errors, the groups of lower and higher errors were created based on a median of AAE of 3.0° (3.8) in the SIT_CC test, and 3.3° (4.3) in the SIT_ECC test. These values are consistent with those reported in previous studies involving repositionings to angles within intermediate ranges of the knee range of motion in the sitting position, and considering similar age groups (Lee & Lim, 2023; Relph & Herrington, 2016).

Regarding the implications of muscle coactivation on the magnitude of errors and directional bias, the proposed hypothesis was only partially confirmed, as no effects concerning error magnitude were found. Still, significant differences were observed between the directional bias groups.

Effectively, the muscle coactivation indices and the mean EMG activations of the *vastus lateralis* and *biceps femoris* from which these indices were calculated did not differ between participants with lower and higher errors in either of the assessed knee JPS tests. In contrast, the directional bias groups showed distinct coactivation patterns, although only in the SIT_CC test. In this case, coactivation was significantly higher among participants who failed the target position in the direction of greater flexion than intended. An analysis of the mean EMG activations revealed that this increased coactivation was due to a higher mean EMG activation of the antagonist (*biceps femoris*), as would be expected, given that these individuals performed more flexion than intended, and a lower activation of the agonist (*vastus lateralis*).

These results suggest that directional bias may be better explained by distinct muscle coactivation mechanisms than the magnitude of errors. In this context, the present findings propose that characterizing JPS uniquely based on AAE, as commonly done in most knee JPS studies, may not be sufficient, and that RAE might play a more relevant role. Nevertheless, to the authors' knowledge, this is the first study to examine differences in muscle coactivation between groups of different magnitudes of errors and directional bias, and further research will be necessary to compare and validate these findings, as well as to investigate which other factors may contribute to different magnitudes of errors between individuals without a history of knee injuries.

Limitations

Some limitations of the study should be acknowledged. First, having the same participants performing the two study sessions may have known disadvantages, such as the learning and carry-over effect. Nevertheless, the authors believe that

the randomization of JPS procedures and muscle fatigue protocols minimized this effect. Regarding the carry-over effect, two weeks between the fatigue protocols were saved to ensure the recovery from the first fatigue protocol. Effectively, previous studies support the idea that an individual recovers from muscle fatigue in periods shorter than one week (Byrne & Eston, 2002; Michaut et al., 2003). Finally, EMG data were not corrected for participants' adipose tissue thickness, which, according to Petrofsky (2008), is a tissue with high electrical resistance and may influence the amplitude of the recorded EMG signal.

Conclusions

This study demonstrated that, in electromyographic assessments, clinicians should expect healthy individuals to exhibit high muscle coactivation indices during knee JPS assessments performed in the sitting position. This may be an essential mechanism to improve movement precision and ensure joint stability. However, after inducing fatigue in either the agonist or antagonist muscle groups, the agonist tends to increase its mean EMG activation, while the antagonist decreases its activation, resulting in a reduction of the coactivation index between these muscles.

Additionally, the present findings indicate that muscle coactivation does not appear to explain why healthy individuals exhibit either lower or higher magnitudes of repositioning errors. In contrast, in a knee JPS test involving a concentric repositioning, directional bias seems to be explained by different muscle coactivation patterns. Specifically, those who fail in the direction of increased flexion exhibit higher coactivation indices, driven by greater mean EMG activation of the antagonist muscle.

These findings suggest that future studies assessing the knee JPS, in addition to reporting repositioning errors using absolute angular errors, should also report relative angular errors, as this measure appears to be more closely related to the respective contributions of the knee extensor and flexor muscles.

References

- Alkjær, T., Simonsen, E. B., Magnusson, S. P., Dyhre-Poulsen, P., & Aagaard, P. (2012). Antagonist muscle moment is increased in ACL deficient subjects during maximal dynamic knee extension. *The Knee*, 19(5), 633-639. <https://doi.org/10.1016/j.knee.2011.12.006>
- Andersen, S. B., Terwilliger, D. M., & Denegar, C. R. (1995). Comparison of Open versus Closed Kinetic Chain Test Positions for Measuring Joint Position Sense. *Journal of sport rehabilitation*, 4(3), 165-171. <https://doi.org/10.1123/jsr.4.3.165>
- Aragão, F. A., Schäfer, G. S., Albuquerque, C. E. d., Vituri, R. F., Azevedo, F. M. d., & Bertolini, G. R. F. (2015). Neuromuscular efficiency of the vastus lateralis and biceps femoris muscles in individuals with anterior cruciate ligament injuries. *Revista Brasileira de Ortopedia*, 50, 180-185. <https://doi.org/10.1016/j.rboe.2015.03.010>
- Aymard, C., Katz, R., Lafitte, C., Le Bozec, S., & Pénicaud, A. (1995). Changes in reciprocal and transjoint inhibition induced by muscle fatigue in man. *Exp Brain Res*, 106(3), 418-424. <https://doi.org/10.1007/bf00231064>
- Azevedo, J., Moreira-Silva, I., Seixas, A., Fonseca, P., Oliveira, J., & Vilas-Boas, J. P. (2024). The Effect of Muscle Fatigue on the Knee Proprioception: A Systematic Review. *Journal of motor behavior*, 56(5), 772–804. <https://doi.org/10.1080/00222895.2024.2341753>
- Azevedo, J., Rodrigues, S., Moreira-Silva, I., Cardoso, R., & Seixas, A. (2024). Acute effects of muscle fatigue on the knee joint-position sense of trained and non-trained individuals. *Athena Health & Research Journal*, 1(1). <https://doi.org/10.62741/ahrj.v1i1.8>
- Balestra, C., Duchateau, J., & Hainaut, K. (1992). Effects of fatigue on the stretch reflex in a human muscle. *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section*, 85(1), 46-52. [https://doi.org/10.1016/0168-5597\(92\)90101-G](https://doi.org/10.1016/0168-5597(92)90101-G)

- Baratta, R., Solomonow, M., Zhou, B., Letson, D., Chuinard, R., & D'ambrosia, R. (1988). Muscular coactivation: the role of the antagonist musculature in maintaining knee stability. *The American journal of sports medicine*, 16(2), 113-122. [https://doi.org/https://doi.org/10.1177/036354658801600205](https://doi.org/10.1177/036354658801600205)
- Baroni, B. M., Geremia, J. M., Rodrigues, R., De Azevedo Franke, R., Karamanidis, K., & Vaz, M. A. (2013). Muscle architecture adaptations to knee extensor eccentric training: rectus femoris vs. vastus lateralis. *Muscle & nerve*, 48(4), 498-506. <https://doi.org/10.1002/mus.23785>
- Begalle, R. L., Distefano, L. J., Blackburn, T., & Padua, D. A. (2012). Quadriceps and hamstrings coactivation during common therapeutic exercises. *J Athl Train*, 47(4), 396-405. <https://doi.org/10.4085/1062-6050-47.4.01>
- Bennell, K., Wee, E., Crossley, K., Stillman, B., & Hodges, P. (2005). Effects of experimentally-induced anterior knee pain on knee joint position sense in healthy individuals. *J. Orthop. Res.*, 23(1), 46-53. <https://doi.org/10.1016/j.orthres.2004.06.008>
- Byrne, C., & Eston, R. (2002). Maximal-intensity isometric and dynamic exercise performance after eccentric muscle actions. *Journal of sports sciences*, 20(12), 951-959. <https://doi.org/10.1080/026404102321011706>
- Carpentier, A., Duchateau, J., & Hainaut, K. (2001). Motor unit behaviour and contractile changes during fatigue in the human first dorsal interosseus. *The Journal of physiology*, 534(3), 903-912. <https://doi.org/10.1111/j.1469-7793.2001.00903.x>
- Clark, N. C., Akins, J. S., Heebner, N. R., Sell, T. C., Abt, J. P., Lovalekar, M., & Lephart, S. M. (2016). Reliability and measurement precision of concentric-to-isometric and eccentric-to-isometric knee active joint position sense tests in uninjured physically active adults. *Physical Therapy in Sport*, 18, 38-45. <https://doi.org/10.1016/j.ptsp.2015.06.005>
- Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Routledge. <https://doi.org/10.4324/9780203771587>

- Da Silva, F., Colson, S. S., Zghal, F., Chorin, F., Guérin, O., & Monjo, F. (2022). Immediate voluntary activation deficits following submaximal eccentric contractions of knee extensors are associated with alterations of the sense of movement. *Scientific Reports*, 12(1), 1-10. <https://doi.org/10.1038/s41598-022-06081-2>
- Da Silva, F., Monjo, F., Zghal, F., Chorin, F., Guérin, O., & Colson, S. S. (2021). Altered Position Sense after Submaximal Eccentric Exercise—inducing Central Fatigue. *Med Sci Sports Exerc*, 53(1), 218-227. <https://doi.org/10.1249/MSS.0000000000002444>
- Des Jarlais, D. C., Lyles, C., Crepaz, N., & Group, T. (2004). Improving the reporting quality of nonrandomized evaluations of behavioral and public health interventions: the TREND statement. *American journal of public health*, 94(3), 361-366.
- Drouin, J. M., Valovich-mcLeod, T. C., Shultz, S. J., Gansneder, B. M., & Perrin, D. H. (2004). Reliability and validity of the Biodex system 3 pro isokinetic dynamometer velocity, torque and position measurements. *European journal of applied physiology*, 91(1), 22-29. <https://doi.org/10.1007/s00421-003-0933-0>
- Duchateau, J., & Baudry, S. (2014). The neural control of coactivation during fatiguing contractions revisited. *J Electromyogr Kinesiol*, 24(6), 780-788. <https://doi.org/10.1016/j.jelekin.2014.08.006>
- Enoka, R. M. (1997). Neural strategies in the control of muscle force. *Muscle & nerve*, 20(S5), 66-69. [https://doi.org/10.1002/\(SICI\)1097-4598\(1997\)5+<66::AID-MUS16>3.0.CO;2-X](https://doi.org/10.1002/(SICI)1097-4598(1997)5+<66::AID-MUS16>3.0.CO;2-X)
- Ervilha, U., Graven-Nielsen, T., & Duarte, M. (2012). A simple test of muscle coactivation estimation using electromyography. *Brazilian Journal of Medical Biological Research*, 45, 977-981. <https://doi.org/10.1590/S0100-879X2012007500092>

- Gribble, P. L., Mullin, L. I., Cothros, N., & Mattar, A. (2003). Role of Cocontraction in Arm Movement Accuracy. *Journal of neurophysiology*, 89(5), 2396-2405. <https://doi.org/10.1152/jn.01020.2002>
- Hassanlouei, H., Arendt-Nielsen, L., Kersting, U. G., & Falla, D. (2012). Effect of exercise-induced fatigue on postural control of the knee. *Journal of electromyography and Kinesiology*, 22(3), 342-347. <https://doi.org/10.1016/j.jelekin.2012.01.014>
- Haynes, A. B., Haukoos, J. S., & Dimick, J. B. (2021). TREND Reporting Guidelines for Nonrandomized/Quasi-Experimental Study Designs. *JAMA Surgery*, 156(9), 879-880. <https://doi.org/10.1001/jamasurg.2021.0552>
- Hermens, H. J., Freriks, B., Disselhorst-Klug, C., & Rau, G. (2000). Development of recommendations for SEMG sensors and sensor placement procedures. *Journal of electromyography and Kinesiology*, 10(5), 361-374. [https://doi.org/https://doi.org/10.1016/S1050-6411\(00\)00027-4](https://doi.org/https://doi.org/10.1016/S1050-6411(00)00027-4)
- Herrington, L. (2005). Knee-Joint Position Sense: The Relationship between Open and Closed Kinetic Chain Tests. *Journal of sport rehabilitation*, 14(4), 356-362. <https://doi.org/10.1123/jsr.14.4.356>
- Kiyama, R., Kawada, M., Tokunaga, K., Ohwatashi, A., Fukudome, K., Yone, K., Yoshimoto, Y., Ohshige, T., & Maeda, T. (2014). The effect of force sensation on the ability to control muscle force during fatigue condition. *Isokinetics and exercise science*, 22(4), 287-293. <https://doi.org/10.3233/ies-140550>
- Kornecki, S. (1992). Mechanism of muscular stabilization process in joints. *Journal of biomechanics*, 25(3), 235-245. [https://doi.org/10.1016/0021-9290\(92\)90023-T](https://doi.org/10.1016/0021-9290(92)90023-T)
- Latash, M. L. (2018). Muscle coactivation: definitions, mechanisms, and functions. 120(1), 88-104. <https://doi.org/10.1152/jn.00084.2018>

- Lee, Y., & Lim, C. (2023). Reference value of knee position sense in weight-bearing and non-weight-bearing conditions. *Knee Surgery & Related Research*, 35(1), 25. <https://doi.org/10.1186/s43019-023-00199-x>
- Lephart, S. M., Pincivero, D. M., & Rozzi, S. L. (1998). Proprioception of the ankle and knee. *Sports medicine*, 25(3), 149-155. <https://doi.org/10.1007/s0003-0149-00350-0>
- Lindstrøm, R., Schomacher, J., Farina, D., Rechter, L., & Falla, D. (2011). Association between neck muscle coactivation, pain, and strength in women with neck pain. *Man Ther*, 16(1), 80-86. <https://doi.org/10.1016/j.math.2010.07.006>
- Lievens, E., Klass, M., Bex, T., & Derave, W. (2020). Muscle fiber typology substantially influences time to recover from high-intensity exercise. *Journal of Applied Physiology*, 128(3), 648-659. <https://doi.org/10.1152/jappphysiol.00636.2019>
- Macgregor, L. J., & Hunter, A. M. (2018). High-threshold motor unit firing reflects force recovery following a bout of damaging eccentric exercise. *PloS one*, 13(4), e0195051. <https://doi.org/10.1371/journal.pone.0195051>
- Mastaglia, F. L. (2012). The relationship between muscle pain and fatigue. *Neuromuscular Disorders*, 22, S178-S180. <https://doi.org/10.1016/j.nmd.2012.10.003>
- Mathiassen, S. E. (1989). Influence of angular velocity and movement frequency on development of fatigue in repeated isokinetic knee extensions. *European journal of applied physiology and occupational physiology*, 59, 80-88. <https://doi.org/10.1007/BF02396584>
- Melnyk, M., & Gollhofer, A. (2007). Submaximal fatigue of the hamstrings impairs specific reflex components and knee stability. *Knee Surgery, Sports Traumatology, Arthroscopy*, 15(5), 525-532. <https://doi.org/10.1007/s00167-006-0226-3>

- Michaut, A., Pousson, M., Millet, G., Belleville, J., & Van Hoecke, J. (2003). Maximal voluntary eccentric, isometric and concentric torque recovery following a concentric isokinetic exercise. *International journal of sports medicine*, 24(1), 51-56. <https://doi.org/10.1055/s-2003-37199>
- Mills, K., Hunt, M. A., Leigh, R., & Ferber, R. (2013). A systematic review and meta-analysis of lower limb neuromuscular alterations associated with knee osteoarthritis during level walking. *Clinical biomechanics*, 28(7), 713-724. <https://doi.org/10.1016/j.clinbiomech.2013.07.008>
- Nagai, T., Schilaty, N. D., Strauss, J. D., Crowley, E. M., & Hewett, T. E. (2018). Analysis of Lower Extremity Proprioception for Anterior Cruciate Ligament Injury Prevention: Current Opinion. *Sports medicine*, 48(6), 1303-1309. <https://doi.org/10.1007/s40279-018-0889-1>
- Olsson, L., Lund, H., Henriksen, M., Rogind, H., Bliddal, H., & Danneskiold-Samsøe, B. (2004). Test–retest reliability of a knee joint position sense measurement method in sitting and prone position. *Adv. Physiother.*, 6(1), 37-47. <https://doi.org/10.1080/14038190310009894>
- Ortiz, A., Olson, S. L., Etnyre, B., Trudelle-Jackson, E. E., Bartlett, W., & Venegas-Rios, H. L. (2010). Fatigue Effects on Knee Joint Stability During Two Jump Tasks in Women. 24(4), 1019-1027. <https://doi.org/10.1519/JSC.0b013e3181c7c5d4>
- Padasala, M., Joksimovic, M., Bruno, C., Melino, D., & Manzi, V. (2020). Muscle injuries in athletes. The relationship between H/Q ratio (hamstring/quadriceps ratio). *Ita J Sports Reh Po*, 7(1), 1478-1498.
- Pedersen, J., Ljubisavljevic, M., Bergenheim, M., & Johansson, H. (1998). Alterations in information transmission in ensembles of primary muscle spindle afferents after muscle fatigue in heteronymous muscle. *Neurosci.*, 84(3), 953-959. [https://doi.org/10.1016/S0306-4522\(97\)00403-X](https://doi.org/10.1016/S0306-4522(97)00403-X)
- Petrofsky, J. (2008). The effect of the subcutaneous fat on the transfer of current through skin and into muscle. *Medical Engineering & Physics*, 30(9), 1168-1176. <https://doi.org/10.1016/j.medengphy.2008.02.009>

- Proske, U. (2023). A reassessment of the role of joint receptors in human position sense. *Exp. Brain Res.*, 241(4), 943-949. <https://doi.org/10.1007/s00221-023-06582-0>
- Psek, J.-A., & Cafarelli, E. (1993). Behavior of coactive muscles during fatigue. *Journal of Applied Physiology*, 74(1), 170-175. <https://doi.org/https://doi.org/10.1152/jappl.1993.74.1.170>
- Relph, N., & Herrington, L. (2016). The effects of knee direction, physical activity and age on knee joint position sense. *The Knee*, 23(3), 393-398. <https://doi.org/http://dx.doi.org/10.1016/j.knee.2016.02.018>
- Riemann, B. L., & Lephart, S. M. (2002). The sensorimotor system, part I: the physiologic basis of functional joint stability. *Journal of athletic training*, 37(1), 71-79. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC164311/pdf/attr_37_01_0071.pdf
- Riemann, B. L., Myers, J. B., & Lephart, S. M. (2002). Sensorimotor system measurement techniques. *J. Athl. Train.*, 37(1), 85-98. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC164313/pdf/attr_37_01_0085.pdf
- Rosenthal, R. (1991). Meta-analytic procedures for social research. In: SAGE Publications, Inc.
- Sangnier, S., & Tourny-Chollet, C. (2007). Comparison of the decrease in strength between hamstrings and quadriceps during isokinetic fatigue testing in semiprofessional soccer players. *International journal of sports medicine*, 28(11), 952-957. <https://doi.org/10.3233/IES-2003-0121>
- Sealed Envelope Ltd. (2024). *Create a blocked randomisation list*. Retrieved 24 Mar 2025 from <https://www.sealedenvelope.com/simple-randomiser/v1/lists>
- Sharma, S. K., Yadav, S. L., Singh, U., & Wadhwa, S. (2017). Muscle Activation Profiles and Co-Activation of Quadriceps and Hamstring Muscles around

- Knee Joint in Indian Primary Osteoarthritis Knee Patients. *J Clin Diagn Res*, 11(5), Rc09-rc14. <https://doi.org/10.7860/jcdr/2017/26975.9870>
- Shokri, P., Eslamian, F., Shakouri, S. K., Ohanian, S., & Jahanjoo, F. (2018). Fatigue Induced Effects after Concentric versus Eccentric Exercises on Sense of Force and Senses of Position among Young Normal Adults-A Controlled Single-Blinded Study. *J. res. med. dent. sci.*, 6(3), 258-267. <https://doi.org/10.24896/jrmds.20186340>
- Smith, S., Rush, J., Glaviano, N. R., Murray, A., Bazett-Jones, D., Bouillon, L., Blackburn, T., & Norte, G. (2021). Sex influences the relationship between hamstrings-to-quadriceps strength imbalance and co-activation during walking gait. *Gait & Posture*, 88, 138-145.
- Smith, S. L., Allan, R., Marreiros, S. P., Woodburn, J., & Steultjens, M. P. M. (2019). Muscle Co-Activation Across Activities of Daily Living in Individuals With Knee Osteoarthritis. *Arthritis Care & Research*, 71(5), 651-660.
- Smith, S. L., Woodburn, J., & Steultjens, M. P. M. (2020). Sex- and osteoarthritis-related differences in muscle co-activation during weight-bearing tasks. *Gait & Posture*, 79, 117-125.
- Stillman, B. C., & McMeeken, J. M. (2001). The role of weightbearing in the clinical assessment of knee joint position sense. *Australian Journal of Physiotherapy*, 47(4), 247-253. [https://doi.org/https://doi.org/10.1016/S0004-9514\(14\)60272-5](https://doi.org/10.1016/S0004-9514(14)60272-5)
- Varrecchia, T., Conforto, S., De Nunzio, A. M., Draicchio, F., Falla, D., & Ranavolo, A. (2022). Trunk Muscle Coactivation in People with and without Low Back Pain during Fatiguing Frequency-Dependent Lifting Activities. 22(4), 1417. <https://www.mdpi.com/1424-8220/22/4/1417>
- Vila-Chã, C., Bovolini, A., Francisco, C., Costa-Brito, A. R., Vaz, C., Rua-Alonso, M., de Paz, J. A., Vieira, T., & Mendonca, G. V. (2023). Acute effects of isotonic eccentric exercise on the neuromuscular function of knee extensors vary according to the motor task: impact on muscle strength profiles, proprioception and balance. *Frontiers in Sports and Active Living*, 5, 1273152. <https://doi.org/10.3389/fspor.2023.1273152>

- Voight, M. L., Hardin, J. A., Blackburn, T. A., Tippet, S., & Canner, G. C. (1996). The effects of muscle fatigue on and the relationship of arm dominance to shoulder proprioception. *J. Orthop. Sports Phys. Ther.*, 23(6), 348-352. <https://doi.org/10.2519/jospt.1996.23.6.348>
- Wu, R., Delahunt, E., Ditroilo, M., Lowery, M. M., & De Vito, G. (2017). Effect of knee joint angle and contraction intensity on hamstrings coactivation. *Medicine & Science in Sports & Exercise*, 49(8), 1668-1676. <https://doi.org/10.1249/MSS.0000000000001273>
- Yanagawa, T., Shelburne, K., Serpas, F., & Pandy, M. (2002). Effect of hamstrings muscle action on stability of the ACL-deficient knee in isokinetic extension exercise. *Clinical biomechanics*, 17(9), 705-712. [https://doi.org/10.1016/S0268-0033\(02\)00104-3](https://doi.org/10.1016/S0268-0033(02)00104-3)

Chapter 6

General Discussion

The aims of this thesis were: (i) to systematically review and summarise the evidence about the effect of muscle fatigue on the knee proprioception of trained and non-trained individuals; (ii) to provide normative values in different knee JPS assessments for healthy young individuals, and to investigate which protocol-related factors produce higher accuracy, as well as the influence of individual factors on the knee JPS; (iii) to investigate the effect of different isolated concentric or eccentric fatigue protocols of the quadriceps or hamstrings on the knee JPS; and (iv) to describe muscle coactivation during knee JPS assessments, before and after muscle fatigue, and to analyse the implications for the magnitude of errors and directional bias.

Peripheral (localized) muscle fatigue has been described to increase the discharge threshold of the muscle spindles, which can compromise proprioceptive input (Balestra et al., 1992; Gribble & Hertel, 2004; Pedersen et al., 1998; Voight et al., 1996). Nevertheless, general fatigue protocols may also affect other mechanisms of the proprioceptive pathways and cause central fatigue, leading to deficits in the central processing of the proprioceptive information (Miura et al., 2004). Effectively, evidence of impaired JPS after localized and general fatigue protocols was demonstrated in the systematic review of **Chapter 2**, in both trained and non-trained individuals (Azevedo et al., 2024).

Specifically considering trained individuals, the studies of Salgado et al. (2015) and Ribeiro et al. (2008) induced general fatigue through a soccer and volleyball match, respectively. In both investigations, the knee JPS of the players significantly worsened after the matches. Nevertheless, a simulated handball match induced in the study of Niederseer et al. (2014) did not produce any effects on the knee JPS, with the authors admitting that the intensity of the simulated match might not have been enough to affect proprioceptive acuity. Also, the

localized fatigue protocol of Azevedo et al. (2018) applied to soccer players did not cause significant increases in the repositioning errors after the fatiguing exercise, with the authors similarly proposing that the protocol was not effective enough to induce fatigue, which was effectively not confirmed by objective measures. Finally, Carrasco et al. (2021) demonstrated that both a localized and general fatigue protocol led to significant increases in repositioning errors in semi-professional soccer players, without reported differences between them.

Some studies found that eccentric fatigue protocols, either general or localized, worsened knee JPS compared to concentric protocols (Bottoni et al., 2015; Givoni et al., 2007; Shokri et al., 2018). The authors hypothesized that the worsening was caused by damage to the muscle fibres due to eccentric exercise, which consequently led to deficits in the input from muscle spindles (Bottoni et al., 2015).

Three studies also investigated the long-term effects of eccentric muscle fatigue of the knee extensors (Paschalis et al., 2007; Torres et al., 2010; Vila-Chã et al., 2011). Paschalis et al. (2007) found significantly increased repositioning errors after the protocol, which had not remained after 24, 48, or 72 hours. On the contrary, Vila-Chã et al. (2011) and Torres et al. (2010) reported that repositioning errors remained increased after 24 and 48 hours, respectively. However, the fatigue protocol for the knee extensors of Vila-Chã et al. (2011) consisted of sets of 25 contractions, and the protocol of Torres et al. (2010) consisted of sets of 30 contractions, while the Paschalis et al. (2007) protocol was of only 15 contractions, suggesting that localized protocols below 25 contractions may not be enough to cause fatigue and impact the knee JPS.

Regarding the effect of muscle fatigue on the knee kinesthesia, it was observed that the impairment on this proprioceptive subcomponent seems to be related to the type of fatigue protocol, since after localized protocols (Da Silva et al., 2022; Torres et al., 2010), TTDPM values significantly increased, while no changes were observed after general protocols (Allison et al., 2016; Roberts et al., 2003).

Finally, the analysis of the studies that investigated the effects of muscle fatigue on the knee force sense revealed that it was significantly affected by fatigue when

assessments were performed to force targets above 20% of the MVIC (Kiyama et al., 2014; Torres et al., 2010). Effectively, Torres et al. (2010) reported a significant decrease in force sense, assessed for a target force of 20% of the MVIC 1 hour after an eccentric fatigue protocol, which has remained until 48 hours. Also, in Kiyama et al. (2014), two target loads were used (10% and 30% of the MVIC), but force sense error significantly increased only in the 30% load. Furthermore, eccentric protocols seemed to have a greater impact on force sense than concentric ones (Shokri et al., 2018).

Since a great variability of parameters regarding knee JPS assessments was seen in the included studies of the systematic review of **Chapter 2**, before investigating the effects of muscle fatigue, the cross-sectional study of **Chapter 3** explored the influence of different parameters that could already affect the accuracy to reposition in baseline assessments. The study revealed that assessments in weight-bearing (standing) produced lower errors than in non-weight-bearing conditions (sitting and prone positions), which is in agreement with previous studies (Andersen et al., 1995; Herrington, 2005; Lephart et al., 1997; Stillman & McMeeken, 2001). This is justified by a larger contribution from mechanoreceptors of surrounding joints and muscles reaching the CNS.

Different accuracies were verified when repositioning to the intermediate angle of 45° and the extreme angle of 20°. Joint mechanoreceptors signal joint position at extreme ranges of the knee ROM (Proske, 2023; Riemann & Lephart, 2002), while muscle mechanoreceptors are more active at intermediate ranges (Docherty et al., 1998), especially between 40° and 80° of knee flexion (Olsson et al., 2004). However, the muscle spindle can provide positional information throughout the entire ROM of a joint (Proske, 2023). Accordingly, there is a cumulative contribution from joint mechanoreceptors and the muscle spindle at extreme ranges (Lee et al., 2003), being expected better proprioceptive acuity at these ranges compared to intermediate ones, where the contribution is exclusively from muscle mechanoreceptors. This was confirmed for the sitting and prone position tests, but the opposite was found in the standing tests. Indeed, in the sitting and prone position tests, higher repositioning errors were observed in the intermediate angle (45°), while in the standing position tests, this was the

target angle with lower errors. In weight-bearing tests, the participant is forced to squat lower to reach the 45° angle than to reach the 20° angle, meaning that the degree of stretching of those involved muscles and respective muscle spindles is greater when repositioning to 45°. The firing frequency of muscle spindles may increase when the stretch range is greater, which has been previously demonstrated in animal studies (Shepherd, 1965) and probably explains the presented results for the weight-bearing tests.

Finally, the study of **Chapter 3** demonstrated that the inclusion of male and female participants in studies involving assessments of the knee JPS has no implications for the accuracy to reposition. However, there is a need for caution when the knee JPS is assessed before and after an intervention like muscle fatigue, as Azevedo et al. (2018) found significantly higher repositioning errors in female soccer players than male players after inducing muscle fatigue. Regarding dominance, the dominant and non-dominant limbs presented similar accuracy, suggesting that assessing only one limb is sufficient.

Although the above-mentioned study demonstrated that weight-bearing tests produced higher accuracy, these tests involve a contribution from the whole limb, not being possible to isolate only the knee joint proprioceptive acuity (Stillman & McMeeken, 2001), which was essential to fulfill the aim of the study of **Chapter 4**. In that sense, the effects of different muscle fatigue protocols on the knee JPS were tested in non-weight-bearing conditions (in sitting and prone positions) in this study. Also, in these two test positions, concentric and eccentric repositionings were maintained, although the results of the study of **Chapter 3** suggested no differences in the repositioning errors between the two types of repositionings. Although the sense of position arises from the proprioceptive information from the agonist and antagonist muscles around the knee joint, considering the muscle spindle function of detecting muscle stretching (Kröger & Watkins, 2021), more contribution may come from the muscle being stretched during a given JPS test. Effectively, one additional aim of the randomized controlled trial of **Chapter 4** was to understand whether a specific muscle fatigue protocol had a greater impact on a particular repositioning test. In that sense, adopting a concentric and eccentric repositioning meant that the knee extensors

and flexors would be stretched while acting as agonists or antagonists during those procedures. However, one of the interpretations of the study's results was that there was a similar effect in the assessed knee JPS tests, regardless of the fatigued muscle group. This suggests that it may not be necessary to perform assessments in so many different test positions or types of repositioning when it is intended to assess the impact of muscle fatigue protocols, as the ones presented in this study. The study of **Chapter 3** revealed that tests in the prone position produced significantly higher errors than in the sitting position. Furthermore, Olsson et al. (2004) reported higher reliability for tests in the sitting position (good to excellent) compared to prone (only fair to good). These authors also proposed that the prone position may be less comfortable, possibly explaining the higher errors and lower reliability. This suggests that when testing the effects of muscle fatigue on knee JPS assessments, prone position tests can be preferentially disregarded compared to sitting tests.

The systematic review of **Chapter 2** also identified three studies that concluded that muscle mechanoreceptors were more affected by muscle fatigue than the joint ones (Ali et al., 2013; Azevedo et al., 2018; Da Silva et al., 2021). Indeed, in the studies of Azevedo et al. (2018) and Ali et al. (2013), a significant increase in repositioning errors after fatigue was found only for the repositioning to 45°, corresponding to an angle where muscle mechanoreceptors are more active (Olsson et al., 2004), while no effects were seen for the extreme angle of 20°. Similar results were reported by Da Silva et al. (2021), as fatigue only affected the repositioning to 70°, while no effects were seen at 30°. Considering these results, the effects of muscle fatigue in the studies of **Chapters 4 and 5** were tested for the target angle of 45°, assuming that muscle mechanoreceptors would be more affected than the joint ones.

Continuing, the results of the study of **Chapter 4** revealed that all four isolated muscle fatigue protocols caused negative effects on the knee JPS, as seen by the increase in the repositioning errors. The concentric fatigue protocol of the quadriceps was the one that produced a negative impact in a greater number of tests, since all four JPS tests registered significant increases in errors, followed by the eccentric fatigue protocol of the quadriceps, which led to a significant

increase in errors in three of the assessed JPS tests. The concentric and eccentric fatigue protocols for the hamstrings only caused a significant increase in errors in two and one JPS tests, respectively. In general, muscle fatigue was confirmed by a force and power decrease and a reduction in the mean EMG activation and frequency of the involved muscles between the initial and final contractions of these fatigue protocols.

Interestingly, Vila-Chã et al. (2011), consistent with the present results, concluded that muscle fatigue led to an impairment of knee JPS assessed in intermediate angles and non-weight bearing conditions. Besides the acute effects, these authors also reported that these effects remained after 24 hours. Additionally, Vila-Chã et al. (2011) tested their participants' JPS in weight-bearing conditions, and JPS seemed unaffected both immediately after and 24 hours after fatigue, which was not consistent with the non-weight-bearing tests' conclusions. These results may suggest that, when performing repositionings in weight-bearing, other non-fatigued muscles with functions in the knee and other lower limb joints may compensate with increased input, mitigating the effects of muscle fatigue on the knee JPS, highlighting a crucial joint stability protection mechanism.

Another essential mechanism to ensure joint stability is muscle coactivation, contributing to increased joint stiffness and, consequently, making the joint less vulnerable to disturbances (Kornecki, 1992). Enoka (1997) has proposed that high levels of muscle coactivation represent a valuable strategy in motions requiring high precision, being therefore essential for accurately repositioning a previously demonstrated angle. Indeed, the results from the study of **Chapter 5** demonstrated high muscle coactivation indices of the knee extensors and flexors in the assessed JPS tests.

The second finding of the study of **Chapter 5** was that muscle fatigue led to a decrease in coactivation indices between the knee extensors and flexors. However, relying exclusively on the coactivation index may not be the most accurate way to interpret the contributions of the involved muscles, particularly under fatigue conditions, as different agonist and antagonist behaviours can

influence the coactivation index. The analysis of mean EMG activations clarified that the reduction in coactivation index following fatigue was due to an increase in the mean EMG activation of the agonist muscle (*vastus lateralis*), combined with a decrease in the mean EMG activation of the antagonist (*biceps femoris*). This pattern appeared to be independent of the fatigued muscle group, as the same trend was observed after both fatigue protocols, regardless of whether fatigue was induced in the agonist or antagonist muscle.

According to Carpentier et al. (2001), the CNS may compensate for the peripheral and deleterious effects of muscle fatigue by increasing the number of recruited motor units, thereby resulting in higher EMG activity, explaining the higher EMG activation of the agonist muscle after fatigue. While this may be a strategy to preserve joint stability, increased EMG activity following fatigue may interfere with segmental position estimation, due to an overload of sensory information for central processing (Kiyama et al., 2014), which supports the observed negative impact of the fatigue protocols of the study of **Chapter 4** on the knee JPS, significantly increasing repositioning errors. Nevertheless, the hypothesis that an increased number of recruited motor units acts as a compensatory mechanism still requires further investigation, ideally using decomposition electromyography, to quantify motor unit recruitment under baseline and post-fatigue conditions.

Finally, regarding the implications of muscle coactivation to the magnitude of errors, these groups were formed based on the median of AAE of 3.0° in the SIT_CC test, and 3.3° in the SIT_ECC test, which values were close to the normative values reported in the study of **Chapter 3**. These results revealed that the muscle coactivation indices and the mean EMG activations of the *vastus lateralis* and *biceps femoris* did not differ between participants with lower and higher errors. In contrast, the directional bias groups showed distinct coactivation patterns, although only in the SIT_CC test. Coactivation was significantly higher among participants who failed the target position in the direction of flexion, due to a higher mean EMG activation of the antagonist (*biceps femoris*), as would be expected, given that these individuals performed greater flexion than supposed, and a lower activation of the agonist (*vastus lateralis*). These results suggest that directional bias may be better explained by distinct muscle coactivation patterns

than the magnitude of errors. In that sense, characterizing JPS uniquely based on AAE, as commonly done in most knee JPS studies, may not be sufficient, with RAE playing a more relevant role. To the authors' knowledge, this is the first study examining differences in muscle coactivation between groups of different magnitudes of errors and directional bias, and further research will be necessary to compare and validate these findings.

General Conclusions

Regarding muscle fatigue, this thesis contributes to a more comprehensive understanding of its effect on the knee JPS, as well as to the identification of the most appropriate tests to achieve greater repositioning accuracy, and the respective contributions of the knee extensors and flexor muscles to this accuracy.

Accordingly, a negative impact of muscle fatigue on the knee proprioception in both trained and non-trained individuals was confirmed. Specifically concerning JPS, both localized and generalized fatigue protocols led to a significant increase in repositioning errors. Regarding kinesthesia, it appears to be more affected by localized fatigue protocols, whereas force sense seems to deteriorate particularly after eccentric fatigue protocols and when assessed at higher target forces.

Normative data covering different knee JPS assessments in healthy young individuals were established, aiming to help clinicians identify and monitor individuals with proprioceptive deficits. Considering the assessments for the angles of 20°/45°, the normative values for the sitting position tests were 3.0°/3.7° for a concentric repositioning test, and 2.7°/3.6° for an eccentric repositioning test. In prone position assessments, the values for the concentric repositioning were 4.0°/4.8°, and 4.8°/4.9° for the eccentric repositioning. Regarding standing position tests, the values of 2.8°/2.5° were obtained for the unipedal test, and 4.3°/3.0° for the bipedal test. Information concerning the influence of protocol-related and individual factors on the JPS accuracy was also provided. Regarding protocol-related factors, it was found: (i) an influence of the test position, with the assessments in the prone position leading to worse accuracy, and the sitting and standing tests leading to better accuracy; (ii) no influence of the type of repositioning (concentric or eccentric); (iii) an influence of the target angles, with the accuracy being higher in extreme angles of sitting and prone position assessments (i.e. in non-weight-bearing), and in intermediate angles of

assessments in the standing position (i.e. in weight-bearing conditions). Regarding individual factors, the results revealed: (i) no influence of dominance, suggesting no need to assess both lower limbs as they appear to have the same acuity; and (ii) no influence of sex, suggesting that this may not be a relevant factor when selecting participants for studies involving JPS assessments.

Then, four different muscle fatigue protocols were tested involving isolated concentric or eccentric contractions of the quadriceps or hamstrings. All protocols produced negative effects on the knee JPS, although some of them produced significant effects on a greater number of JPS tests. Indeed, a concentric fatigue protocol of the quadriceps was the one that affected more tests, followed by the eccentric of the quadriceps, the concentric of the hamstrings, and, finally, the eccentric of the hamstrings. It was also found that regardless of the fatigued muscle group, there was a similar effect in the performance of the assessed knee JPS tests. This suggests that, when it comes to assessing the impact of muscle fatigue protocols as the ones presented, it may not be necessary to assess the knee JPS in so many different test positions or types of repositioning. Moreover, muscle fatigue was confirmed by sEMG, force, and power decrease. In general, EMG results displayed a decrease in the mean and peak EMG as well as in the median frequency, evidencing decreased activation and consequently, decreased input after fatigue. This, combined with the also seen reduced ability to produce force and power, can ultimately contribute to joint instability and injury.

Finally, healthy individuals exhibited high muscle coactivation indices of the knee flexors and extensors during knee JPS assessments performed in the sitting position. This high coactivation may be an essential mechanism to improve movement precision and ensure joint stability. However, after inducing fatigue in either the agonist or antagonist muscle groups, the agonist tended to increase its mean EMG activation, while the antagonist decreased its activation, resulting in a reduction of the coactivation index between these muscles. Additionally, muscle coactivation does not appear to explain why healthy individuals exhibit lower or higher magnitudes of repositioning errors. In contrast, in a knee JPS test involving a concentric repositioning, directional bias seems to be explained by different muscle coactivation patterns. Specifically, those who fail in the direction of flexion

exhibit higher coactivation indices, driven by greater mean EMG activation of the antagonist muscle. These findings suggest that studies assessing the knee JPS, in addition to reporting repositioning errors using absolute angular errors, should also report relative angular errors, as this measure appears to be more closely related to the respective contributions of the knee flexors and extensors.

Chapter 8

References

- Ali, Y., Farzaneh, G., & Homayoon, A. (2013). The Effect Of Fatigue On The Ankle And Knee Proprioception And Dynamic Control Of Posture. *International Journal of Sports Sciences & Fitness*, 3(2), 235-249. <https://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=90508075&lang=pt-pt&site=ehost-live&scope=site>
- Ali, Y., Farzaneh, G., & Homayoon, A. (2013). The Effect Of Fatigue On The Ankle And Knee Proprioception And Dynamic Control Of Posture. *International Journal of Sports Sciences & Fitness*, 3(2), 235-249. <https://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=90508075&lang=pt-pt&site=ehost-live&scope=site>
- Allen, T., Leung, M., & Proske, U. (2010). The effect of fatigue from exercise on human limb position sense. *The Journal of physiology*, 588(8), 1369-1377. <https://doi.org/10.1113/jphysiol.2010.187732>
- Allison, K. F., Abt, J. P., Beals, K., Nagle, E. F., Lovalekar, M. T., Lephart, S. M., & Sell, T. C. (2016). Aerobic capacity and isometric knee flexion strength fatigability are related to knee kinesthesia in physically active women. *Isokinetics & Exercise Science*, 24(4), 357-365. <https://doi.org/10.3233/IES-160638>
- Allison, K. F., Sell, T. C., Benjaminse, A., & Lephart, S. M. (2016). Force sense of the knee not affected by fatiguing the knee extensors and flexors. *Journal of sport rehabilitation*, 25(2), 155-163. <https://doi.org/10.1123/jsr.2014-0298>
- Alkjær, T., Simonsen, E. B., Magnusson, S. P., Dyhre-Poulsen, P., & Aagaard, P. (2012). Antagonist muscle moment is increased in ACL deficient

- subjects during maximal dynamic knee extension. *The Knee*, 19(5), 633-639. <https://doi.org/10.1016/j.knee.2011.12.006>
- Al-Mulla, M., Sepulveda, F., & Colley, M. (2012). sEMG Techniques to Detect and Predict Localised Muscle Fatigue. In M. Schwartz (Ed.), *EMG methods for evaluating muscle and nerve function*. IntechOpen. <https://doi.org/10.5772/25678>
- Andersen, S. B., Terwilliger, D. M., & Denegar, C. R. (1995). Comparison of Open versus Closed Kinetic Chain Test Positions for Measuring Joint Position Sense. *Journal of sport rehabilitation*, 4(3), 165-171. <https://doi.org/10.1123/jsr.4.3.165>
- Aragão, F. A., Schäfer, G. S., Albuquerque, C. E. d., Vituri, R. F., Azevedo, F. M. d., & Bertolini, G. R. F. (2015). Neuromuscular efficiency of the vastus lateralis and biceps femoris muscles in individuals with anterior cruciate ligament injuries. *Revista Brasileira de Ortopedia*, 50, 180-185. <https://doi.org/10.1016/j.rboe.2015.03.010>
- Aydoğ, S. T., Hasçelik, Z., Demirel, H. A., Tetik, O., Aydoğ, E., & Doral, M. N. (2005). The effects of menstrual cycle on the knee joint position sense: preliminary study. *Knee Surgery, Sports Traumatology, Arthroscopy*, 13, 649-653. <https://doi.org/10.1007/s00167-004-0604-7>
- Aymard, C., Katz, R., Lafitte, C., Le Bozec, S., & Pénicaud, A. (1995). Changes in reciprocal and transjoint inhibition induced by muscle fatigue in man. *Exp Brain Res*, 106(3), 418-424. <https://doi.org/10.1007/bf00231064>
- Azevedo, J., Moreira-Silva, I., Seixas, A., Fonseca, P., Oliveira, J., & Vilas-Boas, J. P. (2024). The Effect of Muscle Fatigue on the Knee Proprioception: A Systematic Review. *Journal of motor behavior*, 56(5), 772–804. <https://doi.org/10.1080/00222895.2024.2341753>
- Azevedo, J., Rodrigues, S., & Seixas, A. (2018). Efeito da sobrecarga muscular aguda e crónica no senso de posição articular do joelho [Universidade Fernando Pessoa]. Porto. <http://hdl.handle.net/10284/7060>

- Azevedo, J., Rodrigues, S., & Seixas, A. (2021). The influence of sports practice, dominance and gender on the knee joint position sense. *The Knee*, 28, 117-123. <https://doi.org/10.1016/j.knee.2020.11.013>
- Azevedo, J., Rodrigues, S., Moreira-Silva, I., Cardoso, R., & Seixas, A. (2024). Acute effects of muscle fatigue on the knee joint-position sense of trained and non-trained individuals. *Athena Health & Research Journal*, 1(1). <https://doi.org/10.62741/ahrj.v1i1.8>
- Balestra, C., Duchateau, J., & Hainaut, K. (1992). Effects of fatigue on the stretch reflex in a human muscle. *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section*, 85(1), 46-52. [https://doi.org/10.1016/0168-5597\(92\)90101-G](https://doi.org/10.1016/0168-5597(92)90101-G)
- Baroni, B. M., Geremia, J. M., Rodrigues, R., De Azevedo Franke, R., Karamanidis, K., & Vaz, M. A. (2013). Muscle architecture adaptations to knee extensor eccentric training: rectus femoris vs. vastus lateralis. *Muscle & nerve*, 48(4), 498-506. <https://doi.org/10.1002/mus.23785>
- Barrett, D. S., Cobb, A. G., & Bentley, G. (1991). Joint proprioception in normal, osteoarthritic and replaced knees. *The Journal of bone and joint surgery. British volume*, 73(1), 53-56. <https://doi.org/10.1302/0301-620X.73B1.1991775>
- Baratta, R., Solomonow, M., Zhou, B., Letson, D., Chuinard, R., & D'ambrosia, R. (1988). Muscular coactivation: the role of the antagonist musculature in maintaining knee stability. *The American journal of sports medicine*, 16(2), 113-122. <https://doi.org/https://doi.org/10.1177/036354658801600205>
- Bayramoglu, M., Toprak, R., & Sozay, S. (2007). Effects of osteoarthritis and fatigue on proprioception of the knee joint. *Archives of physical medicine and rehabilitation*, 88(3), 346-350. <https://doi.org/10.1016/j.apmr.2006.12.024>
- Bazneshin, M. M., Amiri, A., Jamshidi, A. A., & Vasaghi-Gharamaleki, B. (2015). Quadriceps muscle fatigue and knee joint position sense in healthy men.

Physical Treatments - Specific Physical Therapy Journal, 5(2), 109-114.
<https://doi.org/10.15412/J.PTJ.07050207>

Begalle, R. L., Distefano, L. J., Blackburn, T., & Padua, D. A. (2012). Quadriceps and hamstrings coactivation during common therapeutic exercises. *J Athl Train*, 47(4), 396-405. <https://doi.org/10.4085/1062-6050-47.4.01>

Bennell, K., Wee, E., Crossley, K., Stillman, B., & Hodges, P. (2005). Effects of experimentally-induced anterior knee pain on knee joint position sense in healthy individuals. *J. Orthop. Res.*, 23(1), 46-53.
<https://doi.org/10.1016/j.orthres.2004.06.008>

Bersotti, F. M., De Melo, T. B., Rafael Skau, J., Mochizuki, L., & Ervilha, U. F. (2022). Fatigue of knee extensor muscles does not alter knee joint position sense. *J. Mech. Med. Biol.*, 22(2), 2250012-2250011-2250012-2250019.
<https://doi.org/10.1142/S0219519422500129>

Bottoni, G., Heinrich, D., Kofler, P., Hasler, M., & Nachbauer, W. (2015). The Effect of Uphill and Downhill Walking on Joint-Position Sense: A Study on Healthy Knees. *Journal of sport rehabilitation*, 24(4), 349-352.
<https://doi.org/10.1123/jsr.2014-0192>

Boyas, S., & Guével, A. (2011). Neuromuscular fatigue in healthy muscle: underlying factors and adaptation mechanisms. *Annals of physical and rehabilitation medicine*, 54(2), 88-108.
<https://doi.org/10.1016/j.rehab.2011.01.001>

Bozkurt, S., ÖZer, Ç., Kuzay, D., DemİR, P., & Meray, J. (2020). The Effect of a Single Session of Eccentric Exercise on Proprioception and Oxidative Stress in Knee Osteoarthritis: A Preliminary Study. *Journal of Physical Medicine & Rehabilitation Sciences*, 23(3), 191-200.
<https://doi.org/10.31609/jpmrs.2020-74173>

Busch, A., Bangerter, C., Mayer, F., & Baur, H. (2023). Reliability of the active knee joint position sense test and influence of limb dominance and sex. *Scientific Reports*, 13(1), 152. <https://doi.org/10.1038/s41598-022-26932-2>

- Byrne, C., & Eston, R. (2002). Maximal-intensity isometric and dynamic exercise performance after eccentric muscle actions. *Journal of sports sciences*, 20(12), 951-959. <https://doi.org/10.1080/026404102321011706>
- Carpentier, A., Duchateau, J., & Hainaut, K. (2001). Motor unit behaviour and contractile changes during fatigue in the human first dorsal interosseus. *The Journal of physiology*, 534(3), 903-912. <https://doi.org/10.1111/j.1469-7793.2001.00903.x>
- Carrasco, L., Espinar, J., Carbonell, F. J., & Martínez-Díaz, I. C. (2021). Local and general fatigue: Effects on knee proprioception in soccer players. *Rev.int.med.cienc.act.fís.deporte*, 21(84), 683-698. <https://doi.org/10.15366/rimcafd2021.84.004>
- Chang, K.-M., Liu, S.-H., & Wu, X.-H. (2012). A wireless sEMG recording system and its application to muscle fatigue detection. *Sensors*, 12(1), 489-499. <https://doi.org/10.3390/s120100489>
- Changela, P. K., Selvamani, K., & Ramaprabhu. (2013). A Study to Evaluate the effect of Fatigue on Knee Joint Proprioception and Balance in Healthy Individuals. *Indian Journal of Physiotherapy & Occupational Therapy*, 7(1), 213-217. <https://search.ebscohost.com/login.aspx?direct=true&db=rzh&AN=102831572&lang=pt-pt&site=ehost-live&scope=site>
- Clark, N. C., Akins, J. S., Heebner, N. R., Sell, T. C., Abt, J. P., Lovalekar, M., & Lephart, S. M. (2016). Reliability and measurement precision of concentric-to-isometric and eccentric-to-isometric knee active joint position sense tests in uninjured physically active adults. *Physical Therapy in Sport*, 18, 38-45. <https://doi.org/10.1016/j.ptsp.2015.06.005>
- Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Routledge. <https://doi.org/10.4324/9780203771587>
- Cowan, J. (2009). *Effect of fatigue on proprioceptive acuity in the asymptomatic untrained male knee*, Unitec New Zealand. New Zealand. <https://hdl.handle.net/10652/1340>

- Craig, J. C., & Rollman, G. B. (1999). Somesthesia. *Annual Review of Psychology*, 50(1), 305-331.
<https://doi.org/10.1146/annurev.psych.50.1.305>
- Da Silva, F., Colson, S. S., Zghal, F., Chorin, F., Guérin, O., & Monjo, F. (2022). Immediate voluntary activation deficits following submaximal eccentric contractions of knee extensors are associated with alterations of the sense of movement. *Scientific Reports*, 12(1), 1-10.
<https://doi.org/10.1038/s41598-022-06081-2>
- Da Silva, F., Monjo, F., Gioda, J., Blain, G. M., Piponnier, E., Corcelle, B., & Colson, S. S. (2022). Knee position sense and knee flexor neuromuscular function are similarly altered after two submaximal eccentric bouts. *European journal of applied physiology*. <https://doi.org/10.1007/s00421-022-05063-6>
- Da Silva, F., Monjo, F., Zghal, F., Chorin, F., Guérin, O., & Colson, S. S. (2021). Altered Position Sense after Submaximal Eccentric Exercise—inducing Central Fatigue. *Med Sci Sports Exerc*, 53(1), 218-227.
<https://doi.org/10.1249/MSS.0000000000002444>
- Da Silva, F., Piponnier, E., Corcelle, B., Blain, G. M., Gioda, J., Colson, S. S., & Monjo, F. (2023). Submaximal fatiguing eccentric contractions of knee flexors alter leg extrapersonal representation. *Heliyon*, 9(8), e18884.
<https://doi.org/10.1016/j.heliyon.2023.e18884>
- DeLang, M. D., Salamh, P. A., Farooq, A., Tabben, M., Whiteley, R., van Dyk, N., & Chamari, K. (2021). The dominant leg is more likely to get injured in soccer players: systematic review and meta-analysis. *Biology of Sport*, 38(3), 397-435. <https://doi.org/10.5114/biolsport.2021.100265>
- Dieling, S., van der Esch, M., & Janssen, T. W. J. (2014). The Effect of Muscle Fatigue on Knee Joint Proprioception in Ballet Dancers and Non-dancers. *Journal of Dance Medicine & Science*, 18(4), 143-148.
<https://doi.org/10.12678/1089-313X.18.4.143>

- Docherty, C. L., Moore, J. H., & Arnold, B. L. (1998). Effects of strength training on strength development and joint position sense in functionally unstable ankles. *J. Athl. Train.*, 33(4), 310-314. <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1320579/pdf/jathtrain00012-0016.pdf>
- Draz, A. H., Atya, A. M., Aboeleneen, A. M., & Elgendy, M. H. (2014). Influence of Acute Back Muscle Fatigue on Repositioning Accuracy of the Knee Joint In healthy subjects. *Journal of Medical Science and Clinical Research*, 2(1), 339-346. <https://jmscr.igmpublication.org/v2-i1/8%20jmscr.pdf>
- Drouin, J. M., Houghlum, P. A., Perrin, D. H., & Gansneder, B. M. (2003). Weight-Bearing and Non-Weight-Bearing Knee-Joint Reposition Sense and Functional Performance. *Journal of sport rehabilitation*, 12(1), 54-66. <https://doi.org/10.1123/jsr.12.1.54>
- Drouin, J. M., Valovich-McLeod, T. C., Shultz, S. J., Gansneder, B. M., & Perrin, D. H. (2004). Reliability and validity of the Biodex system 3 pro isokinetic dynamometer velocity, torque and position measurements. *European journal of applied physiology*, 91(1), 22-29. <https://doi.org/10.1007/s00421-003-0933-0>
- Duchateau, J., & Baudry, S. (2014). The neural control of coactivation during fatiguing contractions revisited. *J Electromyogr Kinesiol*, 24(6), 780-788. <https://doi.org/10.1016/j.jelekin.2014.08.006>
- Dwan, K., Li, T., Altman, D. G., & Elbourne, D. (2019). CONSORT 2010 statement: extension to randomised crossover trials. *BMJ*, 366, l4378. <https://doi.org/10.1136/bmj.l4378>
- Ekstrand, J., Häggglund, M., & Waldén, M. (2011). Epidemiology of muscle injuries in professional football (soccer). *Am J Sports Med*, 39(6), 1226-1232. <https://doi.org/10.1177/0363546510395879>
- Fouladi, R., Rajabi, R., Naseri, N., Pourkazemi, F., & Geranmayeh, M. (2012). Menstrual cycle and knee joint position sense in healthy female athletes.

- Knee Surgery, *Sports Traumatology, Arthroscopy*, 20(8), 1647-1652.
<https://doi.org/10.1007/s00167-011-1811-7>
- Fousekis, K., Tsepis, E., & Vagenas, G. (2010). Lower limb strength in professional soccer players: profile, asymmetry, and training age. *Journal of sports science & medicine*, 9(3), 364-373.
<https://pmc.ncbi.nlm.nih.gov/articles/PMC3761700/pdf/jssm-09-364.pdf>
- Gandevia, S. C. (2001). Spinal and supraspinal factors in human muscle fatigue. *Physiol. Rev.*, 81(4), 1725-1789.
<https://doi.org/10.1152/physrev.2001.81.4.1725>
- Gandevia, S. C., & Burke, D. (1992). Does the nervous system depend on kinesthetic information to control natural limb movements? *Behavioral and Brain Sciences*, 15, 614-632.
<https://doi.org/10.1017/S0140525X0007254X>
- Gear, W. S. (2004). *The effect of increasing levels of exertion of knee joint proprioception* University of Pittsburgh]. Pittsburgh. <http://d-scholarship.pitt.edu/9536/1/gearw12022004.pdf>
- Gear, W. S. (2011). Effect of different levels of localized muscle fatigue on knee position sense. *Journal of Sports Science and Medicine*, 10(4), 725-730.
<https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3761499/pdf/jssm-10-725.pdf>
- Ghiasi, F., & Akbari, A. (2007). Comparison of the effects of open and closed kinematic chain and different target position on the knee joint position sense. *J Med Sci*, 7(6), 969-976.
<https://doi.org/10.3923/jms.2007.969.976>
- Givoni, N. J., Pham, T., Allen, T. J., & Proske, U. (2007). The effect of quadriceps muscle fatigue on position matching at the knee. *The Journal of physiology*, 584(1), 111-119. <https://doi.org/10.1113/jphysiol.2007.134411>

- Giza, E., Mithöfer, K., Farrell, L., Zarins, B., & Gill, T. (2005). Injuries in women's professional soccer. *Br. J. Sports Med.*, 39(4), 212-216. <https://doi.org/10.1136/bjsm.2004.011973>
- Gribble, P. A., & Hertel, J. (2004). Effect of lower-extremity muscle fatigue on postural control. *Arch. Phys. Med. Rehabil.*, 85(4), 589-592. <https://doi.org/10.1016/j.apmr.2003.06.031>
- Gribble, P. L., Mullin, L. I., Cothros, N., & Mattar, A. (2003). Role of Cocontraction in Arm Movement Accuracy. *Journal of neurophysiology*, 89(5), 2396-2405. <https://doi.org/10.1152/jn.01020.2002>
- Haddaway, N. R., Collins, A. M., Coughlin, D., & Kirk, S. (2015). The role of Google Scholar in evidence reviews and its applicability to grey literature searching. *PloS one*, 10(9), e0138237. <https://doi.org/10.1371/journal.pone.0138237>
- Haggerty, A. L., Simon, J. E., Grooms, D. R., & Russell, J. A. (2021). Effect of Load, Angle, and Contraction Type on Clinically Assessed Knee Joint Position Sense. *Journal of sport rehabilitation*, 30(8), 1166-1171. <https://doi.org/10.1123/jsr.2020-0552>
- Hart, J. M., Kerrigan, D. C., Fritz, J. M., & Ingersoll, C. D. (2009). Jogging kinematics after lumbar paraspinal muscle fatigue. *Journal of athletic training*, 44(5), 475-481. <https://doi.org/10.4085/1062-6050-44.5.475>
- Hassanlouei, H., Arendt-Nielsen, L., Kersting, U. G., & Falla, D. (2012). Effect of exercise-induced fatigue on postural control of the knee. *Journal of electromyography and Kinesiology*, 22(3), 342-347. <https://doi.org/10.1016/j.jelekin.2012.01.014>
- Hermens, H. J., Freriks, B., Disselhorst-Klug, C., & Rau, G. (2000). Development of recommendations for SEMG sensors and sensor placement procedures. *Journal of electromyography and Kinesiology*, 10(5), 361-374. [https://doi.org/https://doi.org/10.1016/S1050-6411\(00\)00027-4](https://doi.org/10.1016/S1050-6411(00)00027-4)

- Herrington, L. (2005). Knee-Joint Position Sense: The Relationship between Open and Closed Kinetic Chain Tests. *Journal of sport rehabilitation*, 14(4), 356-362. <https://doi.org/10.1123/jsr.14.4.356>
- IPAQ Research Committee. (2005). Guidelines for data processing and analysis of the International Physical Activity Questionnaire (IPAQ)-short and long forms. https://www.physio-pedia.com/images/c/c7/Quidelines_for_interpreting_the_IPAQ.pdf
- Itokazu, M. (2022). Reliability and accuracy of 2D lower limb joint angles during a standing-up motion for markerless motion analysis software using deep learning. *Medicine in Novel Technology and Devices*, 16, 100188. <https://doi.org/10.1016/j.medntd.2022.100188>
- Johannsen, H., Lind, T., Jakobsen, B., & Krøner, K. (1989). Exercise-induced knee joint laxity in distance runners. *Br. J. Sports Med.*, 23(3), 165-168. <https://doi.org/10.1136/bjism.23.3.165>
- Ju, Y. Y., Wang, C. W., & Cheng, H. Y. K. (2010). Effects of active fatiguing movement versus passive repetitive movement on knee proprioception. *Clinical biomechanics*, 25(7), 708-712. <https://doi.org/10.1016/j.clinbiomech.2010.04.017>
- Khan, W., Khan, M., Alradwan, H., Williams, R., Simunovic, N., & Ayeni, O. R. (2015). Utility of intra-articular hip injections for femoroacetabular impingement: a systematic review. *The Orthopaedic Journal of Sports Medicine*, 3(9), 2325967115601030. <https://doi.org/10.1177/2325967115601030>
- Kim, S., Glaviano, N. R., & Park, J. (2023). Exercise-induced fatigue affects knee proprioceptive acuity and quadriceps neuromuscular function more in patients with ACL reconstruction or meniscus surgery than in healthy individuals. *Knee Surg Sports Traumatol Arthrosc*, 31(12), 5428-5437. <https://doi.org/10.1007/s00167-023-07596-5>

- Kiyama, R., Kawada, M., Tokunaga, K., Ohwatashi, A., Fukudome, K., Yone, K., Yoshimoto, Y., Ohshige, T., & Maeda, T. (2014). The effect of force sensation on the ability to control muscle force during fatigue condition. *Isokinetics and exercise science*, 22(4), 287-293. <https://doi.org/10.3233/ies-140550>
- Kröger, S., & Watkins, B. (2021). Muscle spindle function in healthy and diseased muscle. *Skeletal Muscle*, 11, 3. <https://doi.org/10.1186/s13395-020-00258-x>
- LaStayo, P. C., Woolf, J. M., Lewek, M. D., Snyder-Mackler, L., Reich, T., & Lindstedt, S. L. (2003). Eccentric muscle contractions: their contribution to injury, prevention, rehabilitation, and sport. *Journal of Orthopaedic & Sports Physical Therapy*, 33(10), 557-571. <https://doi.org/10.2519/jospt.2003.33.10.557>
- Lattanzio, P. J., Petrella, R. J., Sproule, J. R., & Fowler, P. J. (1997). Effects of fatigue on knee proprioception. *Clinical Journal of Sport Medicine*, 7(1), 22-27. <https://doi.org/10.1097/00042752-199701000-00005>
- Latash, M. L. (2018). Muscle coactivation: definitions, mechanisms, and functions. *120*(1), 88-104. <https://doi.org/10.1152/jn.00084.2018>
- Lau, K. K. L., Kwan, K. Y. H., Cheung, J. P. Y., Law, K. K. P., Wong, A. Y. L., Chow, D. H. K., & Cheung, K. M. C. (2024). Normative values of spinal and peripheral proprioception in position sense among healthy adolescents and young adults. *Scientific Reports*, 14(1), 31722. <https://doi.org/10.1038/s41598-024-82100-8>
- Lee, H.-M., Liao, J.-J., Cheng, C.-K., Tan, C.-M., & Shih, J.-T. (2003). Evaluation of shoulder proprioception following muscle fatigue. *Clinical biomechanics*, 18(9), 843-847. [https://doi.org/10.1016/S0268-0033\(03\)00151-7](https://doi.org/10.1016/S0268-0033(03)00151-7)
- Lee, T., & Chow, D. (2013). Effects of whole body vibration on spinal proprioception in normal individuals. 35th Annual International Conference of the IEEE EMBS, Osaka, Japan. <https://doi.org/10.1109/EMBC.2013.6610668>

- Lee, Y., & Lim, C. (2023). Reference value of knee position sense in weight-bearing and non-weight-bearing conditions. *Knee Surgery & Related Research*, 35(1), 25. <https://doi.org/10.1186/s43019-023-00199-x>
- Lephart, S. M., Pincivero, D. M., & Rozzi, S. L. (1998). Proprioception of the ankle and knee. *Sports medicine*, 25(3), 149-155. <https://doi.org/10.1007/s0003-0149-00350-0>
- Lephart, S. M., Pincivero, D. M., Giraido, J. L., & Fu, F. H. (1997). The role of proprioception in the management and rehabilitation of athletic injuries. *The American journal of sports medicine*, 25(1), 130-137. <https://doi.org/10.1177/036354659702500126>
- Lephart, S. M., Riemann, B. L., & Fu, F. H. (2000). Introduction to the sensorimotor system. In S. M. Lephart & F. H. Fu (Eds.), *Proprioception and Neuromuscular Control in Joint Stability* (pp. 37–51). IL: Human Kinetics.
- Lewek, M., Rudolph, K., Axe, M., & Snyder-Mackler, L. (2002). The effect of insufficient quadriceps strength on gait after anterior cruciate ligament reconstruction. *Clinical biomechanics*, 17(1), 56-63. [https://doi.org/10.1016/S0268-0033\(01\)00097-3](https://doi.org/10.1016/S0268-0033(01)00097-3)
- Lievens, E., Klass, M., Bex, T., & Derave, W. (2020). Muscle fiber typology substantially influences time to recover from high-intensity exercise. *Journal of Applied Physiology*, 128(3), 648-659. <https://doi.org/10.1152/jappphysiol.00636.2019>
- Lokhande, M. V., Shetye, J., Mehta, A., & Deo, M. V. (2013). Assessment of knee joint proprioception in weight bearing and in non-weight bearing positions in normal subjects. *Journal of Krishna Institute of Medical Sciences University*, 2(2), 94-101. <https://www.jkimsu.com/jkimsu0-vol2no2/jkimsu%20vol%202%20no%202%20july%20-%20dec%202013%2094-101.pdf>

- Macgregor, L. J., & Hunter, A. M. (2018). High-threshold motor unit firing reflects force recovery following a bout of damaging eccentric exercise. *PloS one*, 13(4), e0195051. <https://doi.org/10.1371/journal.pone.0195051>
- Maqsood, M., & Vácz, M. (2023). Immediate Effects of Quadriceps Muscle Kinesiology Taping on Joint Position Sense and Force Sense in Healthy Individuals. *Orthopedics and Sports Medicine*. <https://doi.org/10.20944/preprints202303.0188.v1>
- Marks, R. (1994). Effect of exercise-induced fatigue on position sense of the knee. *Australian Journal of Physiotherapy*, 40(3), 175-181. [https://doi.org/10.1016/S0004-9514\(14\)60576-6](https://doi.org/10.1016/S0004-9514(14)60576-6)
- Marks, R., & Quinney, H. A. (1993). Effect of fatiguing maximal isokinetic quadriceps contractions on ability to estimate knee-position. *Perceptual and motor skills*, 77((3_suppl)), 1195-1202. <https://doi.org/10.2466/pms.1993.77.3f.1195>
- Mastaglia, F. L. (2012). The relationship between muscle pain and fatigue. *Neuromuscular Disorders*, 22, S178-S180. <https://doi.org/https://doi.org/10.1016/j.nmd.2012.10.003>
- Mathiassen, S. E. (1989). Influence of angular velocity and movement frequency on development of fatigue in repeated isokinetic knee extensions. *European journal of applied physiology and occupational physiology*, 59, 80-88. <https://doi.org/10.1007/BF02396584>
- Melnyk, M., & Gollhofer, A. (2007). Submaximal fatigue of the hamstrings impairs specific reflex components and knee stability. *Knee Surgery, Sports Traumatology, Arthroscopy*, 15(5), 525-532. <https://doi.org/10.1007/s00167-006-0226-3>
- Michaut, A., Pousson, M., Millet, G., Belleville, J., & Van Hoecke, J. (2003). Maximal voluntary eccentric, isometric and concentric torque recovery following a concentric isokinetic exercise. *International journal of sports medicine*, 24(1), 51-56. <https://doi.org/10.1055/s-2003-37199>

- Miura, K., Ishibashi, Y., Tsuda, E., Okamura, Y., Otsuka, H., & Toh, S. (2004). The effect of local and general fatigue on knee proprioception. *Arthroscopy: The Journal of Arthroscopic and Related Surgery*, 20(4), 414-418. <https://doi.org/10.1016/j.arthro.2004.01.007>
- Mohammadi, F., Azma, K., Naseh, I., Emadifard, R., & Etemadi, Y. (2013). Military Exercises, Knee and Ankle Joint Position Sense, and Injury in Male Conscripts: A Pilot Study. *Journal of athletic training*, 48(6), 790-796. <https://doi.org/10.4085/1062-6050-48.3.06>
- Muaidi, Q., Nicholson, L., & Refshauge, K. (2009). Do elite athletes exhibit enhanced proprioceptive acuity, range and strength of knee rotation compared with non-athletes? *Scandinavian journal of medicine & science in sports*, 19(1), 103-112. <https://doi.org/10.1111/j.1600-0838.2008.00783.x>
- Nagai, T., Schilaty, N. D., Strauss, J. D., Crowley, E. M., & Hewett, T. E. (2018). Analysis of Lower Extremity Proprioception for Anterior Cruciate Ligament Injury Prevention: Current Opinion. *Sports medicine*, 48(6), 1303-1309. <https://doi.org/10.1007/s40279-018-0889-1>
- Niederseer, D., Mörtl, H., Liebensteiner, M. C., Egger, A., Thaler, C. W., Plöderl, M., Niebauer, J., & Raschner, C. (2014). General fatigue and joint position sense in male elite handball players. *Dtsch. Z. Sportmed.*, 65(6), 149-153. <https://doi.org/10.5960/dzsm.2014.129>
- Nitsure, P., & Prabhu, S. (2015). Study of Differences in Proprioception of Knee Joint with Age, Gender and Lower Limb Dominance in Healthy Asymptomatic Individuals: An Observational Study. *Sports medicine*, 2015(2), 1-5.
- Olsson, L., Lund, H., Henriksen, M., Rogind, H., Bliddal, H., & Danneskiold-Samsøe, B. (2004). Test–retest reliability of a knee joint position sense measurement method in sitting and prone position. *Adv. Physiother.*, 6(1), 37-47. <https://doi.org/10.1080/14038190310009894>

- Ortiz, A., Olson, S. L., Etnyre, B., Trudelle-Jackson, E. E., Bartlett, W., & Venegas-Rios, H. L. (2010). Fatigue Effects on Knee Joint Stability During Two Jump Tasks in Women. *24*(4), 1019-1027. <https://doi.org/10.1519/JSC.0b013e3181c7c5d4>
- Padasala, M., Joksimovic, M., Bruno, C., Melino, D., & Manzi, V. (2020). Muscle injuries in athletes. The relationship between H/Q ratio (hamstring/quadriceps ratio). *Ita J Sports Reh Po*, *7*(1), 1478-1498.
- Page, M. J., Moher, D., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., & Brennan, S. E. (2021). PRISMA 2020 explanation and elaboration: updated guidance and exemplars for reporting systematic reviews. *BMJ*, *372*(160), 1-36. <https://doi.org/10.1136/bmj.n160>
- Paschalis, V., Nikolaidis, M. G., Giakas, G., Jamurtas, A. Z., Pappas, A., & Koutedakis, Y. (2007). The effect of eccentric exercise on position sense and joint reaction angle of the lower limbs. *Muscle & nerve*, *35*(4), 496-503. <https://doi.org/10.1002/mus.20723>
- Paschalis, V., Nikolaidis, M. G., Theodorou, A. A., Deli, C. K., Raso, V., Jamurtas, A. Z., Giakas, G., & Koutedakis, Y. (2013). The effects of eccentric exercise on muscle function and proprioception of individuals being overweight and underweight. *J Strength Cond Res*, *27*(9), 2542-2551. <https://doi.org/10.1519/JSC.0b013e31827fc9a6>
- Paschalis, V., Nikolaidis, M. G., Theodorou, A. A., Giakas, G., Jamurtas, A. Z., & Koutedakis, Y. (2010). Eccentric exercise affects the upper limbs more than the lower limbs in position sense and reaction angle. *Journal of sports sciences*, *28*(1), 33-43. <https://doi.org/10.1080/02640410903334764>
- Pedersen, J., Ljubisavljevic, M., Bergenheim, M., & Johansson, H. (1998). Alterations in information transmission in ensembles of primary muscle spindle afferents after muscle fatigue in heteronymous muscle. *Neurosci.*, *84*(3), 953-959. [https://doi.org/10.1016/S0306-4522\(97\)00403-X](https://doi.org/10.1016/S0306-4522(97)00403-X)

- Pedrinelli, A., da Cunha Filho, G. A. R., Thiele, E. S., & Kullak, O. P. (2013). Estudo epidemiológico das lesões no futebol profissional durante a Copa América de 2011, Argentina. *Rev Bras Ortop.*, 48(2), 131-136. <https://doi.org/10.1016/j.rbo.2012.09.001>
- Pickard, C. M., Sullivan, P. E., Allison, G. T., & Singer, K. P. (2003). Is there a difference in hip joint position sense between young and older groups? *J Gerontol A Biol Sci Med Sci.*, 58(7), 631-635. <https://doi.org/10.1093/gerona/58.7.M631>
- Proske, U. (2019). Exercise, fatigue and proprioception: a retrospective. *Exp Brain Res*, 237(10), 2447-2459. <https://doi.org/10.1007/s00221-019-05634-8>
- Proske, U. (2023). A reassessment of the role of joint receptors in human position sense. *Exp. Brain Res.*, 241(4), 943-949. <https://doi.org/10.1007/s00221-023-06582-0>
- Proske, U., & Gandevia, S. C. (2012). The proprioceptive senses: their roles in signaling body shape, body position and movement, and muscle force. *Physiol Rev.*, 92(4), 1651-1697. <https://doi.org/0.1152/physrev.00048.2011>
- Proske, U., Wise, A., & Gregory, J. (2000). The role of muscle receptors in the detection of movements. *Prog. Neurobiol.*, 60(1), 85-96. [https://doi.org/10.1016/S0301-0082\(99\)00022-2](https://doi.org/10.1016/S0301-0082(99)00022-2)
- Psek, J.-A., & Cafarelli, E. (1993). Behavior of coactive muscles during fatigue. *Journal of Applied Physiology*, 74(1), 170-175. <https://doi.org/https://doi.org/10.1152/jappl.1993.74.1.170>
- Rampichini, S., Vieira, T. M., Castiglioni, P., & Merati, G. (2020). Complexity analysis of surface electromyography for assessing the myoelectric manifestation of muscle fatigue: A review. *Entropy*, 22(5), 529. <https://doi.org/10.3390/e22050529>

- Relph, N., & Herrington, L. (2015). Criterion-related validity of knee joint-position-sense measurement using image capture and isokinetic dynamometry. *Journal of sport rehabilitation*, 24(1). <https://doi.org/10.1123/jsr.2013-0119>
- Relph, N., & Herrington, L. (2016). The effects of knee direction, physical activity and age on knee joint position sense. *The Knee*, 23(3), 393-398. <https://doi.org/http://dx.doi.org/10.1016/j.knee.2016.02.018>
- Ribeiro, F., Mota, J., & Oliveira, J. (2007). Effect of exercise-induced fatigue on position sense of the knee in the elderly. *European journal of applied physiology*, 99(4), 379-385. <https://doi.org/10.1007/s00421-006-0357-8>
- Ribeiro, F., Santos, F., Gonçalves, P., & Oliveira, J. (2008). Effects of volleyball match-induced fatigue on knee joint position sense [Article]. *Eur. J. Sport Sci.*, 8(6), 397-402. <https://doi.org/10.1080/02614360802373060>
- Ribeiro, F., Venâncio, J., Quintas, P., & Oliveira, J. (2011). The effect of fatigue on knee position sense is not dependent upon the muscle group fatigued. *Muscle and Nerve*, 44(2), 217-220. <https://doi.org/10.1002/mus.22018>
- Riemann, B. L., & Lephart, S. M. (2002). The sensorimotor system, part I: the physiologic basis of functional joint stability. *Journal of athletic training*, 37(1), 71-79. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC164311/pdf/attr_37_01_0071.pdf
- Riemann, B. L., Myers, J. B., & Lephart, S. M. (2002). Sensorimotor system measurement techniques. *J. Athl. Train.*, 37(1), 85-98. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC164313/pdf/attr_37_01_0085.pdf
- Roberts, D., Ageberg, E., Andersson, G., & Fridén, T. (2003). Effects of short-term cycling on knee joint proprioception in healthy young persons. *American Journal of Sports Medicine*, 31(6), 990-994. <https://doi.org/10.1177/03635465030310064001>

- Romero-Franco, N., & Jiménez-Reyes, P. (2017). Effects of Warm-Up and Fatigue on Knee Joint Position Sense and Jump Performance. *Journal of motor behavior*, 49(2), 117-122. <https://doi.org/10.1080/00222895.2016.1152222>
- Rosenthal, R. (1991). *Meta-analytic procedures for social research*. In: SAGE Publications, Inc.
- Rozzi, S., Yuktanandana, P., Pincivero, D., & Lephart, S. (2000). Role of fatigue on proprioception and neuromuscular control. In *Proprioception and neuromuscular control in joint stability*. (pp. 375-384). IL: Human Kinetics.
- Salgado, E., Ribeiro, F., & Oliveira, J. (2015). Joint-position sense is altered by football pre-participation warm-up exercise and match induced fatigue. *The Knee*, 22(3), 243-248. <https://doi.org/10.1016/j.knee.2014.10.002>
- Sangnier, S., & Tourny-Chollet, C. (2007). Comparison of the decrease in strength between hamstrings and quadriceps during isokinetic fatigue testing in semiprofessional soccer players. *International journal of sports medicine*, 28(11), 952-957. <https://doi.org/10.3233/IES-2003-0121>
- Sayyadi, P., Minoonejad, H., Seidi, F., Shikhhoseini, R., & Arghadeh, R. (2024). The effectiveness of fatigue on repositioning sense of lower extremities: systematic review and meta-analysis. *BMC Sports Sci Med Rehabil*, 16(1), 35. <https://doi.org/10.1186/s13102-024-00820-w>
- Sealed Envelope Ltd. (2024). Create a blocked randomisation list. Retrieved 24 September 2023 from <https://www.sealedenvelope.com/simple-randomiser/v1/lists>
- Shepherd, G. (1965). Response of the isolated muscle spindle to different rates of stretching. Cold Spring Harbor Symposia on Quantitative Biology,
- Sherrington, C. S. (1920). *The Integrative Action of the Nervous System* (6^a ed.). Yale University Press.
- Shokri, P., Eslamian, F., Shakouri, S. K., Ohanian, S., & Jahanjoo, F. (2018). Fatigue Induced Effects after Concentric versus Eccentric Exercises on

- Sense of Force and Senses of Position among Young Normal Adults-A Controlled Single-Blinded Study. *J. res. med. dent. sci.*, 6(3), 258-267. <https://doi.org/10.24896/jrmds.20186340>
- Skinner, H. B., Wyatt, M. P., Hodgdon, J. A., Conard, D. W., & Barrack, R. L. (1986). Effect of fatigue on joint position sense of the knee. *Journal of Orthopaedic Research*, 4(1), 112-118. <https://doi.org/10.1002/jor.1100040115>
- Slim, K., Nini, E., Forestier, D., Kwiatkowski, F., Panis, Y., & Chipponi, J. (2003). Methodological index for non-randomized studies (MINORS): development and validation of a new instrument. *ANZ journal of surgery*, 73(9), 712-716. <https://doi.org/10.1046/j.1445-2197.2003.02748.x>
- Smith, S., Rush, J., Glaviano, N. R., Murray, A., Bazett-Jones, D., Bouillon, L., Blackburn, T., & Norte, G. (2021). Sex influences the relationship between hamstrings-to-quadriceps strength imbalance and co-activation during walking gait. *Gait & Posture*, 88, 138-145. <https://doi.org/10.1016/j.gaitpost.2021.05.019>
- Smith, S. L., Allan, R., Marreiros, S. P., Woodburn, J., & Steultjens, M. P. M. (2019). Muscle Co-Activation Across Activities of Daily Living in Individuals With Knee Osteoarthritis. *Arthritis Care & Research*, 71(5), 651-660. <https://doi.org/https://doi.org/10.1002/acr.23688>
- Smith, S. L., Woodburn, J., & Steultjens, M. P. M. (2020). Sex- and osteoarthritis-related differences in muscle co-activation during weight-bearing tasks. *Gait & Posture*, 79, 117-125. <https://doi.org/10.1016/j.gaitpost.2020.04.019>
- Sonkodi, B., Hegedűs, Á., Kopper, B., & Berkes, I. (2022). Significantly Delayed Medium-Latency Response of the Stretch Reflex in Delayed-Onset Muscle Soreness of the Quadriceps Femoris Muscles Is Indicative of Sensory Neuronal Microdamage. *Journal of Functional Morphology and Kinesiology*, 7(2), 43. <https://doi.org/10.3390/jfmk7020043>

- Steiner, M., Grana, W., Chillag, K., & Schelberg-Karnes, E. (1986). The effect of exercise on anterior-posterior knee laxity. *Am J Sports Med*, 14(1), 24-29. <https://doi.org/10.1177/036354658601400105>
- Sterne, J. A. C., Savović, J., Page, M. J., Elbers, R. G., Blencowe, N. S., Boutron, I., Cates, C. J., Cheng, H.-Y., Corbett, M. S., Eldridge, S. M., Emberson, J. R., Hernán, M. A., Hopewell, S., Hróbjartsson, A., Junqueira, D. R., Jüni, P., Kirkham, J. J., Lasserson, T., Li, T., McAleenan, A., Reeves, B. C., Shepperd, S., Shrier, I., Stewart, L. A., Tilling, K., White, I. R., Whiting, P. F., & Higgins, J. P. T. (2019). RoB 2: a revised tool for assessing risk of bias in randomised trials. *BMJ*, 366, l4898. <https://doi.org/10.1136/bmj.l4898>
- Stillman, B. C., & McMeeken, J. M. (2001). The role of weightbearing in the clinical assessment of knee joint position sense. *Australian Journal of Physiotherapy*, 47(4), 247-253. [https://doi.org/https://doi.org/10.1016/S0004-9514\(14\)60272-5](https://doi.org/https://doi.org/10.1016/S0004-9514(14)60272-5)
- Teixeira, L. A., De Oliveira, D. L., Romano, R. G., & Correa, S. C. (2011). Leg preference and interlateral asymmetry of balance stability in soccer players. *Research quarterly for exercise and sport*, 82(1), 21-27. <https://doi.org/https://doi.org/10.1080/02701367.2011.10599718>
- Tornero-Aguilera, J. F., Jimenez-Morcillo, J., Rubio-Zarapuz, A., & Clemente-Suárez, V. J. (2022). Central and peripheral fatigue in physical exercise explained: A narrative review. *International Journal of Environmental Research and Public Health*, 19(7), 3909. <https://doi.org/10.3390/ijerph19073909>
- Torres, R., Vasques, J., Duarte, J. A., & Cabri, J. M. H. (2010). Knee proprioception after exercise-induced muscle damage. *International journal of sports medicine*, 31(6), 410-415. <https://doi.org/10.1055/s-0030-1248285>
- Vandenbroucke, J. P., von Elm, E., Altman, D. G., Gøtzsche, P. C., Mulrow, C. D., Pocock, S. J., Poole, C., Schlesselman, J. J., Egger, M., & Initiative, f.

- t. S. (2007). Strengthening the Reporting of Observational Studies in Epidemiology (STROBE): Explanation and Elaboration. *Epidemiology*, 18(6), 805-835. <https://doi.org/10.1097/EDE.0b013e3181577511>
- Vila-Chã, C., Bovolini, A., Francisco, C., Costa-Brito, A. R., Vaz, C., Rua-Alonso, M., de Paz, J. A., Vieira, T., & Mendonca, G. V. (2023). Acute effects of isotonic eccentric exercise on the neuromuscular function of knee extensors vary according to the motor task: impact on muscle strength profiles, proprioception and balance. *Frontiers in Sports and Active Living*, 5, 1273152. <https://doi.org/10.3389/fspor.2023.1273152>
- Vila-Chã, C., Riis, S., Lund, D., Moller, A., Farina, D., & Falla, D. (2011). Effect of unaccustomed eccentric exercise on proprioception of the knee in weight and non-weight bearing tasks. *Journal of electromyography and Kinesiology*, 21(1), 141-147. <https://doi.org/10.1016/j.jelekin.2010.10.001>
- Voight, M. L., Hardin, J. A., Blackburn, T. A., Tippet, S., & Canner, G. C. (1996). The effects of muscle fatigue on and the relationship of arm dominance to shoulder proprioception. *J. Orthop. Sports Phys. Ther.*, 23(6), 348-352. <https://doi.org/10.2519/jospt.1996.23.6.348>
- Wu, R., Delahunt, E., Ditroilo, M., Lowery, M. M., & De Vito, G. (2017). Effect of knee joint angle and contraction intensity on hamstrings coactivation. *Medicine & Science in Sports & Exercise*, 49(8), 1668-1676. <https://doi.org/10.1249/MSS.0000000000001273>
- Yanagawa, T., Shelburne, K., Serpas, F., & Pandy, M. (2002). Effect of hamstrings muscle action on stability of the ACL-deficient knee in isokinetic extension exercise. *Clinical biomechanics*, 17(9), 705-712. [https://doi.org/10.1016/S0268-0033\(02\)00104-3](https://doi.org/10.1016/S0268-0033(02)00104-3)