

The Biomechanics of Movement in Golf

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Primeiramente, expresso o meu mais sincero reconhecimento a todos aqueles que, no contexto acadêmico, se dedicam diariamente à exigente e nobre missão de ensinar, orientar e inspirar. É através desse compromisso contínuo, muitas vezes silencioso, que se constroem percursos, se desenvolvem competências e se transformam vidas. Ao meu orientador, **Professor Doutor João Paulo Vilas-Boas**, manifesto uma profunda e sentida gratidão. Pela sua presença constante, pelo rigor científico que sempre promoveu, pela confiança demonstrada e pelo acompanhamento ao longo de todo este percurso. Mesmo perante os desafios e ajustamentos que se foram impondo, manteve inalteráveis a sua integridade, o seu compromisso e a sua dedicação. Constituiu, em todos os momentos, um exemplo ímpar do que significa orientar, ensinar e acreditar. Ao meu co-orientador **Pedro Fonseca**, quero deixar-lhe um sincero agradecimento por toda a disponibilidade, dedicação e apoio demonstrados ao longo do meu trabalho. A sua presença constante e incansável em todos os momentos foi fundamental para o desenvolvimento deste percurso, e sou profundamente grato por todo o acompanhamento prestado.

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Com todo o amor,

O Pai

E com profunda e permanente gratidão a Deus pela união da nossa família.

Resumo

O desempenho no golfe depende da capacidade de gerar velocidade elevada da cabeça do taco, mantendo simultaneamente precisão, consistência e controlo técnico. O *swing* do golfe é um movimento complexo de corpo inteiro, que exige uma interação coordenada entre os membros inferiores, a pélvis, o tronco, os membros superiores, os punhos e o taco. Apesar da biomecânica do golfe ter sido amplamente investigada em jogadores adultos e experientes, sabe-se menos sobre a forma como os jogadores de golfe jovens de elite organizam o seu *swing* quando se adaptam a tacos com diferentes exigências mecânicas e técnicas. Esta dissertação teve como objetivo analisar os determinantes biomecânicos do *swing* de golfe, integrando a evidência científica disponível e avaliando empiricamente as diferenças cinemáticas entre o Driver e o Ferro 7 em jogadores de golfe de elite sub-18.

A dissertação foi organizada em formato baseado em artigos. Em primeiro lugar, foi realizada uma revisão sistemática com o objetivo de sintetizar os principais determinantes biomecânicos associados ao desempenho do *swing* de golfe, incluindo a coordenação intersegmentar, a sequência proximal-distal, o acoplamento pélvis-tronco, o X-Factor, a interação com o solo, o controlo neuromuscular, a trajetória da cabeça do taco e as cargas mecânicas relacionadas com o risco de lesão. Em segundo lugar, foi desenvolvido um estudo cinemático empírico que comparou os *swings* realizados com o Driver e com o Ferro 7 em jogadores de golfe jovens de elite, focando-se nas variáveis de *setup*, na duração do *swing*, na estrutura das fases, nas velocidades máximas e no *X-Factor*.

A revisão sistemática demonstrou que o desempenho no *swing* de golfe é multifatorial e não pode ser explicado por uma única variável biomecânica. Um desempenho eficiente depende da transferência coordenada de energia ao longo da cadeia cinética, de um controlo postural estável, de uma temporização adequada e da capacidade de adaptar a organização do movimento às exigências da tarefa. O estudo empírico mostrou que o *Driver* originou uma base de apoio mais ampla e profunda, velocidades máximas superiores durante as fases de *backswing*, *downswing* e contacto com a bola, bem como um maior *X-Factor* no topo do *backswing*, em comparação com o Ferro 7. No entanto, a duração total do *swing* e a duração relativa das respetivas fases não diferiram significativamente entre os tacos, sugerindo que os jogadores de golfe jovens de elite preservam uma estrutura temporal estável, ao mesmo tempo que adaptam a postura e a

produção de velocidade às características do taco. Para além disso, o *X-Factor* não se correlacionou significativamente com a velocidade do *swing*, indicando que a separação pélvis-tronco não deve ser interpretada como um preditor isolado do desempenho em jovens jogadores de golfe.

Assim, esta dissertação reforça que o *swing* de golfe em jovens jogadores de elite deve ser compreendido como um movimento coordenado, adaptativo e sensível ao desenvolvimento. Os resultados evidenciam a importância da coordenação intersegmentar, do ritmo, do controlo motor, de um desenvolvimento físico adequado e da seleção individualizada do equipamento no treino de golfe juvenil.

Palavras-chave: Golfe; biomecânica; *swing*; cinemática; atletas jovens; *X-Factor*; Driver; Ferro 7.

Abstract

Golf performance depends on the ability to generate high clubhead speed while maintaining accuracy, consistency, and technical control. The golf swing is a complex whole-body movement that requires coordinated interaction between the lower limbs, pelvis, trunk, upper limbs, wrists, and club. Although golf biomechanics has been widely investigated in adult and skilled players, less is known about how elite youth golfers organize their swing when adapting to clubs with different mechanical and technical demands. This thesis aimed to analyze the biomechanical determinants of the golf swing by integrating the available scientific evidence and empirically assessing the kinematic differences between the Driver and the 7-iron in elite under-18 golfers.

The thesis was organized in an article-based format. First, a systematic review was conducted to synthesize the main biomechanical determinants associated with golf swing performance, including intersegmental coordination, proximal-to-distal sequencing, pelvis-trunk coupling, X-Factor, ground interaction, neuromuscular control, clubhead trajectory, and injury-related mechanical loads. Second, an empirical kinematic study compared swings performed with the Driver and the 7-iron in elite youth golfers, focusing on setup variables, swing duration, phase structure, maximum velocities, and X-Factor.

The systematic review showed that golf swing performance is multifactorial and cannot be explained by a single biomechanical variable. Efficient performance depends on the coordinated transfer of energy through the kinetic chain, stable postural control, appropriate timing, and the ability to adapt movement organization to task demands. The empirical study showed that the Driver produced a wider and deeper stance, higher maximum velocities during the backswing, downswing, and ball contact phases, and a greater X-Factor at the top of the backswing compared with the 7-iron. However, total swing duration and the relative duration of swing phases did not differ significantly between clubs, suggesting that elite youth golfers preserve a stable temporal structure while adapting posture and velocity production to club characteristics. In addition, X-Factor was not significantly correlated with swing speed, indicating that pelvis-trunk separation should not be interpreted as an isolated predictor of performance in young golfers.

Overall, this thesis reinforces that the golf swing in elite youth players should be understood as a coordinated, adaptive, and developmentally sensitive movement. The findings highlight the importance of intersegmental coordination, rhythm, motor control,

appropriate physical development, and individualized equipment selection in youth golf training.

Keywords: Golf; biomechanics; swing; kinematics; youth athletes; X-Factor; Driver; Iron 7.

Lista de abreviaturas, siglas e símbolos

1RM	—	One-repetition maximum
2D	—	Two-dimensional
3D	—	Three-dimensional
ACL	—	Anterior cruciate ligament
AROM	—	Active range of motion
AUC	—	Area under the curve
BLSTM	—	Bidirectional long short-term memory
CHS	—	Clubhead speed
CHV	—	Clubhead velocity
CMJ	—	Countermovement jump
CNN	—	Convolutional neural network
CoG / COG	—	Center of gravity
CoM	—	Center of mass
CRP	—	Continuous relative phase
DoF	—	Degrees of freedom
DR1	—	Delayed Release 1
DR2	—	Delayed Release 2
EA	—	Elevation angle
EMG	—	Electromyography
ER	—	Early release
FMS	—	Functional Movement Screen
FSP	—	Functional swing plane
FTG	—	Fast swing speed group
GMS	—	Golf Movement Screen
GRF	—	Ground reaction forces
HHT	—	Hilbert-Huang Transform
HMP	—	Hand movement plane
Hz	—	Hertz
IMU	—	Inertial measurement unit
L4-L5	—	Lumbar segment between the fourth and fifth lumbar vertebrae
L5-S1	—	Lumbar-sacral segment between the fifth lumbar vertebra and the first sacral vertebra

LDLR — Directional Lean-Lean-Rotation
 LMA — Laban Movement Analysis
 MGS — Minimalist Golf Swing
 MP — Movement plane
 MVC — Maximum voluntary contraction
 MVIC — Maximum voluntary isometric contraction
 n — Number of participants, studies, or observations
 NEPT — Normalized eccentric peak torque
 OHS — Overhead squat test
 p — Statistical significance value
 PCA — Principal component analysis
 PRISMA — Preferred Reporting Items for Systematic Reviews and Meta-Analyses
 r — Correlation coefficient
 RBSB — Rotation-Flexion-Side Bending
 RC — Recocking
 RFD — Rate of force development
 ROM — Range of motion
 SPI — Swing Performance Index
 STG — Slow swing speed group
 UCM — Uncontrolled Manifold Analysis
 WB — Weight-bearing
 X-Factor — Angular difference between pelvic rotation and upper-trunk rotation
 X-Factor stretch — Increase in pelvis-trunk separation during the early downswing
 Z-Y-X — Euler/Cardan rotation sequence used in three-dimensional movement analysis

Índice

Agradecimentos	iii
Resumo	iv
Abstract.....	vi
Lista de abreviaturas, siglas e símbolos.....	viii
Índice	x
Índice de tabelas	xii
Índice de figuras	xiii
Chapter 1. General Introduction	14
Chapter 2. Systematic Review.....	20
2.1. Introduction	23
2.2. Methodology.....	25
2.3. Results and Discussion	26
2.3.1. Intersegmental Organization of the Swing	27
2.3.2. Motor Control, Stability, and Weight Distribution.....	87
2.3.3. Performance Parameters	102
2.3.4. Adaptations and Training Strategies.....	119
2.4. Conclusion	135
2.5. Limitations and Future Perspectives.....	137
2.6. References	138
Chapter 3. Empirical Study	164
3.1 Introduction	166
3.2. Methods	167
3.2.1. Participants	167
3.2.2. Experimental setup	167
3.2.3. Data Analysis.....	168
3.2.4. Statistical Analysis	169

3.3. Results	170
3.4. Discussion.....	171
3.5. Conclusions	173
3.6. Conflict Of Interests	174
3.7. Funding.....	174
3.8. References	174
Chapter 4. General Discussion	177
Chapter 5. General Conclusions	187
General References	192

Índice de tabelas

Table 2.1. Characteristics of the selected studies addressing biomechanical analysis of the golf swing.....	42
Table 2.2. Characteristics of the selected studies addressing motor control, balance, and weight distribution.....	91
Table 2.3. Characteristics of the selected studies addressing analysis of performance parameters.....	108
Table 2.4. Characteristics of the selected studies addressing training adaptations and intervention strategies.....	124
Table 3.1. Statistical results of the comparison between a swing performed with a driver or an Iron 7 club.....	170

Índice de figuras

Figure 2.1. PRISMA flow diagram showing the study selection process.....	26
Figure 3.1. Representation of the experimental setup and retroreflective marker placement on the club. The backswing and downswing club trajectory are highlighted, and the stance width and depth defined.....	169

Chapter 1. General Introduction

Golf is a technically demanding sport in which precision, motor coordination, and the ability to generate controlled power play a decisive role in performance. Although it is often perceived as a sport with lower metabolic demands when compared with continuous-effort sports, golf involves complex motor patterns that require strength, mobility, balance, postural control, and intermuscular coordination (Wells et al., 2009). Beyond its competitive dimension, golf participation has been associated with physical, psychological, and social benefits, including the maintenance of functional capacity, mobility, concentration, and overall well-being (Murray et al., 2017). The wide international popularity of the sport further reinforces its relevance as an object of study within sport sciences (Farrally et al., 2003).

Among the various technical actions in golf, the swing plays a central role, as it directly influences shot distance, accuracy, and consistency. The golf swing should not be understood as an isolated movement of the upper limbs or the club, but rather as a whole-body motor action organized through a complex kinetic chain (Dillman & Lange, 2002). This chain involves the sequential interaction of the lower limbs, pelvis, trunk, shoulders, upper limbs, wrists, and club, allowing the progressive generation and transfer of energy toward impact with the ball (Milburn, 1982). The effectiveness of this action therefore depends on the player's ability to produce force from the ground, transfer it through the body segments, and apply it at the precise moment of impact (Nesbit & Serrano, 2005). The segmental transfer mechanism of the golf swing has often been explained through the proximal-to-distal principle. According to this principle, efficient movement tends to begin in the proximal segments, such as the pelvis and trunk, and then progress toward the distal segments, including the upper limbs, wrists, and club (Milburn, 1982). This temporal organization allows angular velocity to be amplified throughout the kinetic chain and contributes to greater clubhead speed at impact (Tinmark et al., 2010). However, speed production does not depend solely on isolated muscular force, but also on the temporal coordination between body segments, postural stability, and the ability to control club orientation during the final phase of the movement (Morrison et al., 2016). From a biomechanical perspective, the golf swing is particularly relevant because it combines demands for both power and precision. Clubhead speed is a key variable for shot distance because it directly influences initial ball velocity and the amount of energy transferred during club-ball contact (Fletcher & Hartwell, 2004). Nevertheless, greater clubhead speed alone does not guarantee better performance, since shot effectiveness also depends on clubface orientation, angle of attack, clubhead path, and the point of impact

on the clubface (Hume et al., 2005). The relationship between power and control is therefore one of the central characteristics of golf performance.

Biomechanics makes it possible to study these mechanisms objectively by quantifying kinematic and kinetic variables associated with movement. Kinematic analysis enables the assessment of displacements, joint ranges of motion, angular velocities, phase durations, and relationships between body segments (Egret et al., 2003). Kinetic analysis, in turn, allows the study of force production, joint moments, ground reaction forces, and weight-transfer strategies during the swing (Ball & Best, 2007). The integration of these dimensions provides a more complete understanding of mechanical efficiency, clubhead speed, impact accuracy, and technical consistency in golfers (Chu et al., 2010).

One of the most widely studied concepts in golf biomechanics is the X-Factor, defined as the angular difference between upper-trunk rotation and pelvic rotation, particularly at the top of the backswing (Hume et al., 2005). This parameter has been interpreted as an indicator of pelvic-thoracic dissociation and of the capacity to store elastic energy during the preparatory phase of the swing (Cheetham et al., 2001). Separation between the pelvis and trunk may favor power production during the downswing when it is integrated within an efficient temporal sequence (Myers et al., 2008). However, the relationship between X-Factor and performance is not linear, since different calculation methods may produce distinct values and limit direct comparisons between studies (Brown et al., 2013; Y.-H. Kwon et al., 2013). For this reason, Joyce et al. (2010) emphasized the importance of methodological standardization in the three-dimensional assessment of the X-Factor.

Interaction with the ground is another essential component for understanding golf swing performance. Ground reaction forces contribute to the generation of rotational moments and to the transfer of energy throughout the kinetic chain (Ball & Best, 2007). More proficient players tend to show more efficient weight-transfer patterns, shifting support from the trail foot to the lead foot during the downswing in a controlled and functional manner (Queen et al., 2013). Han et al. (2019) demonstrated that the lead foot and trail foot perform distinct functions in the production of force moments, with the lead foot being more closely associated with the generation of ground reaction force and the trail foot with pivot control. This coordination between support, rotation, and weight transfer contributes to increasing clubhead speed without compromising postural stability.

The technical consistency of the swing also depends on the golfer's ability to control clubhead trajectory and clubface orientation at impact. Experienced players tend to display lower variability in ground reaction forces and more consistent motor patterns,

which may contribute to greater shot repeatability (Jones et al., 2024). The consistency of the swing plane and hub path has been associated with accuracy and movement stability, particularly in players with higher technical proficiency (Morrison et al., 2018a, 2018b; O'Brien et al., 2020). In addition, clubface orientation at impact is a decisive variable for ball direction, and more experienced golfers are able to maintain greater control of this orientation even at high clubhead speeds (Ichikawa et al., 2022).

The neuromuscular dimension is also a determinant of golf performance. Core strength, lower-limb power, hip mobility, and lumbopelvic stability influence the ability to generate speed and control movement (Sell et al., 2007). Johansen et al. (2023) found that golfers with greater isometric strength, higher neuromuscular power, and greater trunk rotational power achieved higher clubhead speeds. Similarly, Kim et al. (2019) showed that strength-training programs may improve body composition, maximal strength, and driving distance. These findings reinforce the idea that golf performance depends not only on technique, but also on the physical capacities that support efficient swing execution.

In youth golfers, the relationship between physical capacities and performance is particularly important. Brožka et al. (2023) observed that development in height, lean mass, jump power, and knee-extensor moment was related to changes in clubhead speed in junior players. These findings suggest that physical maturation may directly influence swing performance development. In addition, Gryc et al. (2023) identified differences between male and female youth golfers in variables such as pelvic rotation, thoracic rotation, and X-Factor, reinforcing the need to consider age, sex, and maturation when conducting biomechanical analyses of young athletes.

Beyond performance, golf biomechanics has an important role in injury prevention. The swing places considerable loads on the lumbar spine, hips, knees, shoulders, elbows, and wrists, mainly due to the repetitive nature of the movement and the high rotational velocities involved (Hosea & Gatt, 1996). Lim et al. (2012) demonstrated that compressive forces in the lumbar region during the downswing may exceed six times body weight. When these loads are associated with motor-control deficits, asymmetries, or mobility limitations, the risk of musculoskeletal overload may increase. For this reason, biomechanical analysis is useful not only for optimizing distance or speed, but also for identifying potentially harmful technical patterns and guiding preventive strategies (Meira & Brumitt, 2010).

Despite the considerable growth of research on golf swing biomechanics, important gaps remain. Much of the literature focuses on adults, professional players, or amateur golfers,

often using heterogeneous samples in terms of age, technical level, and sport experience (Hume et al., 2005). These studies have contributed to the identification of general swing determinants, such as the proximal-to-distal sequence, X-Factor, weight transfer, and clubhead speed (Chu et al., 2010). However, evidence concerning elite youth golfers remains less integrated, particularly during phases of physical, technical, and neuromuscular development. This limitation is important because young athletes should not be analyzed merely as smaller versions of adults; their maturational, coordinative, and neuromuscular characteristics may modify the way they produce and control the swing (Brožka et al., 2023).

Another relevant gap concerns the adaptation of the swing to different clubs. The Driver and 7-iron differ in length, mass, technical purpose, and control demands. The Driver is typically used to maximize distance and requires high clubhead speed, whereas the 7-iron is more closely associated with trajectory control, accuracy, and impact consistency. Previous studies have shown that club type may influence kinematic, temporal, and coordinative swing parameters (Egret et al., 2003). Joyce (2017a) showed that although the X-Factor may not differ significantly between clubs, segmental interactions may vary between swings performed with the Driver and with irons. More recently, Liu et al. (2025) found that the proximal-to-distal sequence tends to be preserved across different clubs, but with specific temporal and mechanical differences, suggesting distinct adaptations between movements oriented toward power and movements oriented toward precision.

The comparison between the Driver and 7-iron in elite youth golfers is therefore particularly relevant. If athletes maintain a similar kinematic organization across clubs, this may indicate the existence of relatively stable and consolidated motor patterns. Conversely, if differences are observed in pelvic rotation, thoracic rotation, X-Factor, or clubhead speed, this may indicate specific adaptation strategies according to the mechanical demands of each club. This issue has relevant implications for training, as it may help clarify whether technical development should prioritize general movement patterns or club-specific adaptations according to equipment and shot objectives.

Within this framework, the general aim of this thesis is to analyze the biomechanical determinants of the golf swing by integrating existing scientific evidence and empirically assessing the kinematic differences between the Driver and the 7-iron in elite youth golfers. This approach combines a systematic review of the literature with an empirical study applied to a population that remains underexplored in golf biomechanics.

More specifically, this thesis aims to systematize the scientific literature on golf swing biomechanics, identifying the main contributions related to kinematics, kinetics, motor control, strength, stability, performance, and injury prevention. It also seeks to identify the kinematic, neuromuscular, and coordinative determinants associated with swing performance, with particular attention to clubhead speed, X-Factor, the proximal-to-distal sequence, weight transfer, and player-ground interaction. In the empirical component, the thesis compares swings performed with the Driver and the 7-iron in elite under-18 golfers, analyzing how club characteristics influence movement organization. Additionally, it examines the relationship between X-Factor and clubhead speed, discussing whether pelvis-trunk separation should be interpreted as a direct determinant of performance in this population or as one component of a broader biomechanical system.

The thesis is organized in an article-based format. Chapter 2 presents a systematic review of golf swing biomechanics, synthesizing the available evidence on intersegmental organization, motor control, stability, weight distribution, performance parameters, training strategies, and injury prevention. Chapter 3 presents the empirical study, focused on the comparative analysis of kinematic swing variables with the Driver and the 7-iron in elite youth golfers. Chapter 4 provides a general discussion, critically integrating the findings from the systematic review and the empirical study, with particular attention to implications for training, applied biomechanics, and the development of young athletes. Finally, Chapter 5 presents the general conclusions, highlighting the main contributions of the work, its limitations, and possible directions for future research.

Chapter 2. Systematic Review

Biomechanics of the Golf Swing: A Systematic Review

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Abstract

Golf biomechanics is essential for understanding the mechanical, neuromuscular, and coordinative determinants that influence swing efficiency and performance. In recent decades, the analysis of this mechanics has enabled the characterization of the mechanisms underlying power production, impact accuracy, and injury prevention, providing an objective framework for the technical and physical optimization of players. This systematic literature review aimed to synthesize the available knowledge and identify the critical variables influencing performance in the golf swing. Following the PRISMA guidelines, Preferred Reporting Items for Systematic Reviews and Meta-Analyses, the search was conducted in PubMed, Web of Science, ProQuest, and Scopus, including publications up to October 31, 2025. A total of 227 empirical studies were included and grouped into four thematic categories: intersegmental organization of the swing, motor control, stability and weight distribution, performance parameters, and training adaptations and strategies.

The findings show that swing efficiency depends on intersegmental coordination, controlled weight transfer, and synchronized muscle activation. Experienced players demonstrate greater pelvis-thorax integration, better use of elastic energy, and lower variability in ground reaction force. Variables such as clubface angle, trajectory, and ball speed are reliable predictors of accuracy and distance. Training strategies focused on strength, flexibility, and technical optimization have shown effectiveness in improving performance and mitigating injury risk.

This review consolidates a multidimensional scientific basis for understanding and optimizing golf performance.

Keywords: golf; biomechanics; kinematics; kinetics; motor control; swing

2.1. Introduction

Golf is a sport that combines precision, coordination, and strength (Wells et al., 2009), and is played by approximately 55 million people worldwide (Farrally et al., 2003). In addition to the enjoyment associated with its practice, golf has been recognized for its significant physical and mental health benefits, promoting well-being, mobility, and concentration (Murray et al., 2017).

The golf swing is the central technical element of the sport and is characterized by a highly coordinated movement requiring the integration of strength, flexibility, balance, and neuromotor control. This movement involves a complex kinetic chain, in which multiple body segments contribute to the generation and transfer of energy from the ground to the ball. The biomechanics of the swing seeks to understand this energy transfer and to identify the factors that influence performance, consistency, and injury prevention (Dillman & Lange, 2002). During the backswing, elastic energy is stored through trunk rotation and the application of force moments to the club, creating mechanical potential for the subsequent phase. During the downswing, the coordinated release of this energy, associated with the proximal-distal sequence, enables acceleration of the clubhead, whose velocity is directly proportional to the kinetic energy transferred to the ball (Fletcher & Hartwell, 2004; S. M. Nesbit & M. Serrano, 2005). Thus, the mechanical power of the swing results from the product of the force exerted and the velocity of execution, reflecting the efficiency of the kinetic chain (Baechle & Earle, 2008).

Among the most relevant kinematic determinants is pelvis-thorax separation, known as the X-factor, defined as the difference in axial rotation between the pelvis and the upper trunk at the top of the backswing (Hume et al., 2005). This segmental dissociation allows elastic energy to be stored in the muscular and tendinous tissues, enhancing rotational force during the downswing (E. R. Komi et al., 2007; Komi, 2000). However, the literature presents ambiguous findings regarding the relationship between the X-factor and performance, reinforcing the need for more integrated studies (Cheetham et al., 2001; Myers et al., 2008).

Weight transfer and the application of ground reaction forces, GRF, are also key determinants of power generation and stability (K. Ball & R. Best, 2007; Robin M. Queen et al., 2013). Elite players demonstrate more efficient transfer patterns from the trail foot to the lead foot during the downswing, resulting in higher club speed and lower postural variability. The analysis of ground reaction forces, GRF, has made it possible to identify

distinct movement styles, such as the front-foot and reverse styles, associated with different acceleration and control strategies (Ball & Best, 2012).

From a technical perspective, clubhead trajectory and angle of attack at impact directly influence accuracy, spin, and the stability of ball flight (Hume et al., 2005; Y. H. Kwon et al., 2013). These parameters are closely linked to segmental rotation and the position of the center of pressure, reflecting the degree of coordination between kinematics and applied force (McNitt-Gray et al., 2013b).

Golf biomechanics has also played a fundamental role in injury prevention. The swing imposes high compressive and shear loads on the lumbar spine, shoulders, and wrists, frequently associated with low back pain and repetitive strain injuries (Edwards et al., 2020; Lindsay & Vandervoort, 2014). Training programs focused on core strengthening, hip mobility, and pelvic stability have demonstrated effectiveness in reducing injury risk and improving mechanical efficiency (Lehman, 2006; Meira & Brumitt, 2010).

Technological advances have significantly driven biomechanical research in this sport. Three-dimensional motion capture systems, 3D motion capture, and surface electromyography, EMG, allow precise characterization of kinematics and muscle activation during the different phases of the swing (Egret et al., 2003; Jarque-Bou et al., 2021). More recently, the use of inertial measurement units, IMUs, and machine learning algorithms has enabled analysis in real-world contexts, outside the laboratory, providing real-time metrics on the orientation, acceleration, and rotation of body segments (Dorschky et al., 2023; Liu et al., 2021). These emerging approaches have the potential to revolutionize technical training, the personalization of strategies, and performance monitoring.

Given the biomechanical complexity of the swing and its multifactorial influence on performance, this systematic review aims to synthesize the main scientific evidence on the determinants of golf performance, organizing them into four domains: intersegmental organization of the swing, motor control and weight distribution, performance parameters, and training adaptations and strategies. This analysis seeks to integrate biomechanical, neuromuscular, and technical contributions, offering a comprehensive view of the mechanisms that sustain efficiency and performance, as well as a conceptual basis for research and practical application in this sport.

2.2. Methodology

This literature review followed the PRISMA methodology, Preferred Reporting Items for Systematic Reviews and Meta-Analyses (Moher et al., 2009), with the collection of scientific articles conducted in the following electronic databases: PubMed, Web of Science, ProQuest, and Scopus. The search included studies published up to October 31, 2025, and used the following Boolean search string: “((((kinematics) OR (kinetics)) OR (EMG)) OR (force)) OR (movement pattern) OR (biomechanics)) AND (golf)”. Only empirical scientific articles were considered for analysis.

Study selection was performed in Rayyan in two stages. In the first stage, titles and abstracts were screened to identify publications that met the following inclusion criteria: studies addressing golf biomechanics, focused on golf players, and written in English. Before the initial screening, all records obtained from the different databases were exported to Rayyan and subjected to automatic duplicate checking. Duplicate entries were identified and removed based on matching title, authors, and year of publication. The final set of articles was then manually reviewed to ensure the absence of redundancies.

In the second stage, the articles were read in full to verify their suitability for the objective of the review. Studies were excluded if they analyzed other sports, investigated putting exclusively, involved injured athletes, or explored only the influence of equipment, such as clothing and footwear, on golf biomechanics.

The selected studies were organized into four main categories according to their thematic focus: intersegmental organization of the swing; motor control, stability, and weight distribution; performance parameters; and training adaptations and strategies. The data extracted from each study were systematized in tables containing information on the authors and year of publication, sample studied, experimental procedures, and main findings.

The analysis of the studies was conducted descriptively and comparatively, identifying the main methodologies used in the literature to assess golf biomechanics. Data categorization allowed for a structured approach, facilitating the understanding of the methods applied and contributing to a detailed synthesis of the approaches used in golf biomechanics research.

2.3. Results and Discussion

This systematic review aimed to analyze and discuss the main scientific contributions related to golf biomechanics, based on a set of rigorous inclusion and exclusion criteria. The analysis of the results was structured into subthemes to facilitate the organization and interpretation of the findings, highlighting scientific advances in each area as well as the gaps that remain in the literature. A total of 226 articles were selected for analysis (Figure 2.1), which were divided into five main subthemes: intersegmental organization of the swing (132 articles); motor control, stability, and weight distribution (33 articles); performance parameters (31 articles); and training adaptations and strategies (30 articles). In the following topics, the evidence related to the main biomechanical elements of golf will be presented and discussed, providing a broad overview of the impact of these variables on the performance and technique of players with different skill levels.

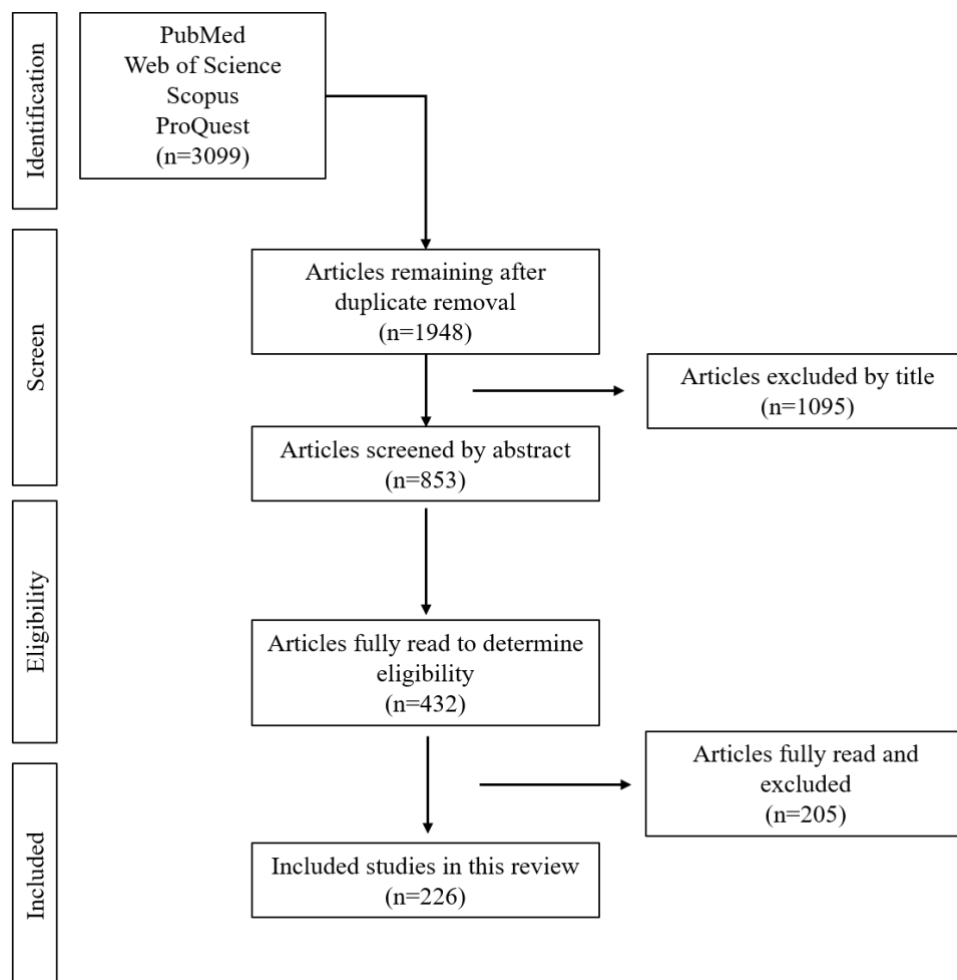


Figure 2.1. PRISMA flow diagram showing the study selection process.

2.3.1. Intersegmental Organization of the Swing

The analysis of the intersegmental organization of the golf swing allows the identification of biomechanical factors that are essential for performance. Among the studies included in this review, several analyzed the interaction of kinematic variables of body segments and the influence of physical and technical factors on players' performance (Table 2.1).

2.3.1.1.1. Proximal-distal sequence and interaction force moment

The efficiency of the golf swing is based on the proximal-distal sequence, which ensures the progressive transfer of energy and force moment between the segments of the kinetic chain. Milburn (1982) confirmed the “principle of summation of segmental velocities,” demonstrating that efficient movement begins at the hip and progresses to the trunk, upper limbs, and club. In this context, the interaction force moment corresponds to the mechanical effect produced by internal and external forces acting between adjacent body segments, allowing the rotation initiated in proximal segments, such as the pelvis and trunk, to contribute to the progressive acceleration of distal segments, such as the upper limbs and the club. Burden et al. (1998) observed that players with sequential pelvis-shoulder rotation generate greater force moment and drive velocity. Tinmark et al. (2010) corroborated the successive increase in angular velocity of the segments up to the clubhead, highlighting the importance of the interaction force moment in mechanical transfer between segments.

Healy et al. (2011) highlighted that greater shoulder flexion and extension, as well as greater extension of the lead upper limb during the downswing, increase shot distance. In right-handed players, this corresponds to the left upper limb, whereas in left-handed players it corresponds to the right upper limb. Teu et al. (2006) identified the trunk as the main generator of club velocity, followed by wrist extension and upper-limb abduction. Chu et al. (2010) reinforced that pelvis-thorax separation, the X-factor, upper-limb lag, and weight displacement are determinants of ball speed. Madrid et al. (2020) showed that a shorter downswing and greater separation between the pelvis and trunk increase clubhead speed, CHS.

Tinmark et al. (2010) and Rusdiana et al. (2021) confirmed the role of proximal-distal coordination, showing that experienced players exhibit greater rotation amplitude and angular velocity of the hips and shoulders. Liu et al. (2025) found that the proximal-distal sequence is preserved with the driver, 5-iron, and 7-iron, but with temporal differences:

the driver shows longer transitions and greater energy accumulation, whereas shorter irons anticipate the peak angular velocity of the distal segments, favoring greater accuracy. Ground reaction forces vary between clubs, reflecting different acceleration and control strategies.

McGuire et al. (2024) analyzed the short game and observed that the proximal-distal sequence is maintained, although it is less consistent in short shots. Increased target distance prolongs the backswing and reduces the downswing, confirming that coordination between the pelvis, trunk, and upper limbs adjusts to the amplitude of the movement, influencing velocity and transition time. Choi, Lee, et al. (2016) demonstrated that the difference in rotation between the support-side hip and the trunk during the downswing determines club velocity, being more evident in professionals. Morrison et al. (2016) added that experienced players show greater motor synergy to control clubhead orientation.

Peterson et al. (2016) and Peterson and McNitt-Gray (2018) showed that use of the driver generates greater angular impulse in the joints of the lower limbs, particularly along the kinetic chain that includes the ankle, knee, and hip, and may also involve contributions from the lumbopelvic complex, reinforcing the importance of multi-joint coordination. Mahadas et al. (2018), Balzerson et al. (2016), and Brown et al. (2020) applied computational models that identified timing and joint force moments as determinants for maximizing final club velocity.

Efficient coordination between segments is therefore the main factor distinguishing elite players, enabling greater energy transfer and accuracy without joint overload.

3.1.1.2. Pelvis-trunk coupling, X-factor, X-factor stretch, and Z-Y-X sequence

Coupling between the pelvis and trunk is a key element for generating power and stability. Horan and Kavanagh (2012) observed strong coupling between the thorax and pelvis during the downswing, associated with swing consistency. Gould et al. (2021) found that better postural control and spinal mobility are correlated with better performance.

Milburn (1982) and Burden et al. (1998) had already demonstrated that sequential pelvis-trunk rotation amplifies the intersegmental force moment. Khuyagbaatar et al. (2019) identified right knee adduction, right shoulder external rotation, and left elbow extension as predictors of the X-factor, reinforcing the multisegmental nature of the movement.

Brown et al. (2013) and Y.-H. Kwon et al. (2013) highlighted that different methods for calculating the X-factor produce distinct results, making direct comparisons difficult.

Joyce et al. (2010) validated the Z-Y-X sequence of Euler/Cardan angles, which describes segmental orientation through three successive rotations, axial rotation, flexion-extension, and lateral bending, as the most appropriate approach for measuring the X-factor and pelvic segment movements. Lamb and Pataky (2018) showed that X-factor stretch increases with greater effort during the downswing, indicating the role of the stretch-shortening cycle in swing power. Joyce (2017b) observed that driver and 5-iron swings showed different segmental patterns despite similar X-factor values, and Joyce, Chivers, et al. (2016) associated strong coupling between the thoracic and pelvic segments with higher club velocities and lower launch angles.

Baek et al. (2025) compared two three-dimensional angular calculation methods for the trunk, RBSB and LDLR, and showed that the LDLR model, centered on the longitudinal axis, describes axial movement with greater precision and less interference between angles. The new model reduces numerical distortion of the X-factor and improves postural analysis, suggesting the need to update measurement protocols.

McHugh et al. (2022) added that greater separation between the pelvis and trunk and greater hip flexibility translate into higher velocities and longer distances. McHugh et al. (2024) confirmed that the X-factor at impact, together with pelvic rotational velocity and trunk deceleration, explains a large proportion of the variability in distance and ball speed. More proficient players showed greater eccentric deceleration capacity of the thoracic segment, that is, active control of the reduction in angular velocity through eccentric muscular action, reinforcing the role of temporal control in power generation. Han et al. (2019) and Park et al. (2018) showed that the consistency of this coordination reduces angular variability and improves dynamic control, whereas Kim et al. (2022) found that ball position modifies the X-factor and joint angles in the sagittal plane.

2.3.1.1.3. Consistency of the swing plane and hub path

Consistency of the swing plane and hub trajectory, the club's point of rotation, is fundamental for accuracy and repeatability. Sanders and Owens (1992) showed that elite players maintain consistent hub trajectories, whereas junior players show greater variability. A. Morrison et al. (2018) demonstrated that a clubhead trajectory fitted to a more eccentric ellipse is associated with greater accuracy and consistency.

Coleman and Anderson (2007) and Coleman and Rankin (2005) observed that low-handicap players adjust the swing plane more effectively and that the lead upper limb and shoulder girdle do not follow a fixed plane, but rather an adaptive functional plane. Kwon

et al. (2012) identified variations in the functional swing plane, FSP, and in the shoulder and upper-limb planes, showing that experienced players exhibit greater control in semi-planar swings.

Andrew Morrison et al. (2018) and Joyce (2017b) observed that club type alters segmental interaction and the plane of movement, requiring specific technical adjustments. Kwon et al. (2021) identified three main swing patterns based on the relationships between the hand planes and the FSP, with direct implications for training interventions. Cheng et al. (2025) classified four wrist-release styles. The Delayed Release 1 pattern showed the most complete proximal-distal sequence and greater kinematic efficiency while maintaining club velocity. Earlier release styles depend more on upper-limb movement and showed lower intersegmental coordination. Bairan Li et al. (2023) demonstrated that sloped terrain restricts center-of-gravity movement, affecting stability and the swing plane.

Brown et al. (2020) and Zhou et al. (2022) reinforced that coordination of movement planes and the rotational velocity of the pelvis and trunk differentiate professionals from amateurs, with the swing performance index, SPI, showing high discriminative validity. Fossati et al. (2010) added that 3D motion capture systems allow the reconstruction of trajectories with high precision and accessibility.

2.3.1.2. Lower limbs and interaction with the ground

Performance in the golf swing depends greatly on the stability, strength, and coordination of the lower limbs, which are responsible for energy transfer and control of the base of support. Support, mobility, and hip rotation have been associated with movement efficiency, force moment production, dynamic balance, and injury prevention (Bechler et al., 1995; Frontani et al., 2022; Gulgin et al., 2009; Park et al., 2018).

Frontani et al. (2022) observed that professional players show greater acceleration of the left knee at frequencies of 1-2 Hz and 2-3 Hz, indicating greater dynamic control. Park et al. (2018) found that variability in the knee valgus angle is higher in less skilled players, especially at the beginning of the downswing, evidencing limitations in the control of the target-side knee. Bechler et al. (1995) reinforced that the extensors and abductors of the trail hip, together with the adductor magnus of the lead hip, initiate pelvic rotation, demonstrating the importance of intermuscular coordination. Gulgin et al. (2009) showed that internal rotation of the lead hip is greater than external rotation of the trail hip, confirming the role of support-hip mobility in power generation.

Han et al. (2019) described that the force moments generated by the lead and trail feet play distinct roles: the lead foot contributes to GRF, whereas the trail foot contributes to the pivot moment. Peterson and McNitt-Gray (2019) demonstrated that the “lead leg elevated” condition increases angular impulse of the lead lower limb, modifying the balance of linear and angular forces. Hooker et al. (2018) found that wider stances and 30° foot angles significantly reduce the external knee adduction moment without compromising swing speed, suggesting simple postural adjustments to reduce joint loads. Lim et al. (2012) reported that compressive forces in the lumbar spine, at the L4-L5 level, may exceed six times body weight, and that shear forces require high muscular control to avoid overload. Dale and Brumitt (2016) showed that a shortened swing reduces the X-factor and compressive vertebral forces, although it also decreases shot velocity and distance, representing a compromise between protection and performance.

Purevsuren et al. (2020) observed that players with greater loads on the anterior cruciate ligament exhibit higher external knee adduction moments and greater trunk movement after impact, highlighting the need for appropriate force distribution. Kim and So (2017) found that professionals show a smaller minimum angle in the support knee, reflecting better joint stability during weight transfer.

Coordination between the hips and pelvis is also decisive. Chaemkhan et al. (2025) observed that higher plantar pressures on the medial metatarsus of the trail lower limb and on the lateral arch of the lead lower limb are associated with greater transfer of energy from the trunk, whereas excessive pressure on the hallux of the lead lower limb reduces efficiency and increases the risk of lumbar overload. Balanced plantar distribution is therefore determinant for energy and stability control during the downswing.

Suwondit et al. (2022) demonstrated that core muscle strength and power correlate with pelvis and hip biomechanics, indicating that central stability directly affects performance. Alderslade et al. (2015) found a positive, but non-significant, correlation between passive and dynamic range of motion in the support hip, suggesting that isolated mobility does not predict efficiency. Gulgin et al. (2010) identified significant asymmetries between the hips, with greater internal and external rotation in the support hip, which may predispose players to joint overload.

Studies on strength and physical training also emphasize the role of the lower limbs. Johansen et al. (2023) found that greater isometric strength and neuromuscular power are associated with higher swing speeds. Kim et al. (2019) demonstrated that an eight-week strength-training program improved body composition, maximal strength, 1RM, and

drive distance. Suhara et al. (2023) observed that hip and trunk extensor strength is positively correlated with clubhead speed, and Marta et al. (2016) reported greater muscle activation of the lower limbs, especially on the left side, in skilled players and with longer clubs.

Interaction with the ground is another critical element. Jones et al. (2024) showed that experienced players present lower intraindividual variability in ground reaction forces, suggesting more consistent motor patterns. McNitt-Gray et al. (2013a) observed that reducing shot distance compromises the magnitude of horizontal forces but maintains their direction, reinforcing the importance of force regulation. Wang et al. (2015) associated vertical reaction force in the left foot and activation of the latissimus dorsi with impact accuracy, whereas Farnoosh and Ostadabbas (2022) used artificial intelligence to segment swing phases, showing that consistent force-application patterns contribute to performance.

Zemková et al. (2019) and Gryc et al. (2023) reported asymmetries in rotational power and pelvic rotation between sexes and maturation levels, indicating specific adaptations. Mitchell et al. (2003) and Horan et al. (2011; 2010) observed that senior and female players show lower range of motion and greater rotational variability, reinforcing the need for individualized training.

2.3.1.3. Upper segments and club control

The upper segments, namely the shoulders, elbows, wrists, and hands, play a determining role in the final transfer of energy and in controlling club orientation. The coordination of these segments directly influences CHS, impact accuracy, and injury prevention.

Joyce, Burnett, et al. (2016) demonstrated that wrist kinematics is a critical factor for CHS, regardless of the club used, with early wrist release and greater axial trunk rotation being associated with the use of clubs with a lower impact point. Betzler et al. (2012) showed that more flexible club shafts result in greater wrist angular velocity and faster recovery, although without significant differences in shot performance. McNally et al. (2019) complemented this information by indicating that the club flexion pattern is individual and should guide equipment customization.

Takagi et al. (2017) observed that the inclination and rotation of the club shaft influence face orientation at impact, with direct repercussions on accuracy. D'Arcy et al. (2021) identified that stronger grips, from -15° to -30° , increase accuracy and distance, whereas weaker grips, from $+15^{\circ}$ to $+30^{\circ}$, reduce performance. Langlais and Broker (2014) and

Kawashima and Nagata (1989) showed that grip force is greater in the dominant hand and peaks during the acceleration phase, decreasing at impact; elite players exhibit repetitive pressure patterns in the little, ring, and middle fingers, which contributes to greater club stability.

Shoulder and elbow biomechanics are also decisive. Healy et al. (2011) observed that greater shoulder flexion and extension and elbow extension of the lead upper limb increase distance with the 5-iron. Nabil et al. (2020) found that players with elbow injuries present lower eccentric force moment of the shoulder abductors and external rotators, suggesting stability deficits in the upper chain. Jobe et al. (1986) emphasized that synchronized activation of the subscapularis and pectoralis major is essential during the acceleration phase, confirming the role of the upper kinetic chain.

Farber et al. (2009) observed that professional players activate the pronator teres muscle of the lead upper limb more intensely, whereas amateur players activate the trail upper limb, revealing technical differences in club control. Watkins et al. (1996) and Pink et al. (1990; 1993) showed that the abdominal muscles, latissimus dorsi, and gluteal muscles stabilize the trunk and support upper-limb movement, ensuring maximal energy transfer. Fan et al. (2025) explored muscular synergies in different push-up variations and observed that neuromuscular coordination is modular, maintaining two main synergies but with activation varying according to hand position. These findings have implications for functional training and for the stability of the upper kinetic chain in golf.

Sorbie et al. (2018) and Verikas et al. (2016) reported that activation of the erector spinae and postural muscles reaches its peak during acceleration, with professional players exhibiting more synchronized patterns concentrated at impact, whereas amateur players show more dispersed activation. Morrison et al. (2016) reinforced that motor synergy in controlling clubhead orientation is more relevant than rigid technique, favoring consistent and adaptable movements.

Joyce (2017b) showed that, although the X-factor and crunch factor, a combination of lateral flexion and body rotation during the downswing that creates significant compressive force in the lumbar region, do not differ between the driver and 5-iron, segmental interactions vary, with faster swings associated with greater X-factor stretch and lower lateral trunk flexion. Joyce, Chivers, et al. (2016) found a positive correlation between axial rotation of the trunk and lower trunk, associated with higher club velocities and lower launch angles, reinforcing the role of upper segmental coupling.

Han et al. (2019) and Kwon et al. (2021) confirmed that the downswing movement sequence shows high interindividual variability, with different acceleration patterns of the upper segments, reflecting individual technical styles. Kwon et al. (2012) and Andrew Morrison et al. (2018) showed that elite players exhibit greater control and consistency in clubhead trajectory, and O'Brien et al. (2020) highlighted that optimizations of the hub and clubhead trajectory, both in the laboratory and in the field, increase impact velocity within individual kinematic constraints.

B. Li et al. (2023) and Fuyu et al. (2019) showed that elite players present lower variability in shaft position and greater convergence of turning points, with more precise clubface orientation at impact. Ichikawa et al. (2022) reinforced that experienced players maintain greater consistency of the face-to-target angle even at high velocities, demonstrating refined technical control.

The role of age and sex is also relevant. Mitchell et al. (2003) observed that senior players show lower shoulder rotational range of motion, whereas Horan et al. (2011; 2010) and Zheng et al. (2008) found biomechanical differences between men and women, with men exhibiting higher angular velocities and women adapting wrist and elbow kinematics. Gryc et al. (2023) showed that, in young players, thoracic rotation is negatively correlated with club velocity, suggesting that the X-factor may have different effects depending on sex and maturation level.

Ward et al. (2015) and Choi et al. (2014) showed that, despite good overall coordination, hip kinematics in the sagittal plane does not directly correlate with ball trajectory, and that a smoother downswing, associated with controlled lower joints, characterizes experienced players. Han et al. (2019) and Bradshaw et al. (2009) reinforced that consistency in key positions, such as the top of the backswing, is indicative of greater motor control and higher technical proficiency.

2.3.1.4. Internal load, risk, and mitigation strategies

The golf swing combines high mechanical loads, particularly on the lumbar spine, hips, and knees. Managing these forces and implementing mitigation strategies are essential to preserve performance and reduce injury risk.

Lim et al. (2012) reported that compressive loads at L4-L5 may exceed six times body weight, while anterior and medial shear forces are significant, requiring efficient muscular control to protect the spine. [Author missing] (2024) showed that players with better performance in the overhead squat test exhibit lower lumbar angular velocity and

lower shear forces at L4-L5 and L5-S1 during the downswing, indicating better trunk control and lower risk of low back pain. The overhead squat test, OHS, thus appears to be a functional predictor of core stability and spinal load in golf. Dale and Brumitt (2016) found that a shortened swing reduces the X-factor and intervertebral forces, decreasing lumbar stress, although at the expense of lower velocity and distance.

Bechler et al. (1995) highlighted that the extensors and abductors of the trail hip, together with the adductor magnus of the lead hip, initiate pelvic rotation, promoting stability and reducing joint load. Purevsuren et al. (2020) observed that players with higher anterior cruciate ligament, ACL, loads exhibit higher knee adduction moments and greater trunk movement after impact, suggesting that poor distribution of internal forces may increase injury risk.

Zemková et al. (2019) demonstrated that trunk rotational power is significantly higher on the dominant side, reflecting the impact of functional asymmetries on performance and overload risk. Gulgin et al. (2010) identified marked differences in rotation between the lead hip and the swing hip, indicating asymmetric patterns that may predispose players to joint overload. Mitchell et al. (2003) found that senior players present lower shoulder range of motion, which may compromise efficiency and increase demand on other joints. Marta et al. (2016) showed that longer clubs require greater muscle activation, increasing the load on the hamstrings and paravertebral muscles. Langlais and Broker (2014) observed variations in grip force during the swing, with peaks during acceleration and a sharp decrease at impact, implying repeated effort of the finger and wrist flexor muscles. Betzler et al. (2012) added that club shaft stiffness affects wrist kinematics, although without significant impact on the forces applied.

Brown et al. (2020) and Andrew Morrison et al. (2018) demonstrated that optimizing the temporal sequence of force moment generation and transfer between segments and intersegmental timing reduces the total load required to generate velocity, increasing efficiency without sacrificing power. Nasirzadeh et al. (2025) tested a passive exosuit that stores elastic energy during the backswing and releases it during the downswing, increasing rotational power and club velocity by approximately 2.5%, without altering technique. The device functioned as an “external tendon,” showing potential for power and proprioception training. Han et al. (2019) showed that the lead and trail feet play distinct roles in producing rotational moments: the former generates the moment produced by ground reaction forces, associated with body rotation production, whereas the latter stabilizes and controls the pivot, which is essential to avoid unilateral overload.

Lim et al. (2012) and Purevsuren et al. (2020) converge in showing that regulation of horizontal and vertical forces in the target-side foot directly influences joint load. McNitt-Gray et al. (2013b) reinforced that reducing shot distance decreases the magnitude of horizontal forces without altering their orientation, allowing joint impact to be minimized without losing coordination.

Suwondit et al. (2022) observed a correlation between core strength and pelvis and hip stability, suggesting that core strengthening is determinant in mitigating overload. Sorbie et al. (2018), Pink et al. (1990; 1993), and Watkins et al. (1996) highlighted that coordinated activation of the abdominal, gluteal, and erector spinae muscles stabilizes the trunk, reduces stress in the lumbar region of the spine, and improves force transfer.

Verikas et al. (2016) and Ebashi and Shibayama (1981) showed that professional players exhibit peaks of muscle activation concentrated at impact, whereas amateur players present more dispersed discharges, resulting in lower efficiency and greater overload risk. Suhara et al. (2023) and Lee et al. (2023) reinforced that the strength of hip and trunk extensors is positively associated with club velocity, indicating that strengthening these muscle groups improves performance and protects against injuries.

Nabil et al. (2020) warned that deficits in eccentric force moment of the shoulder rotators and abductors are linked to recurrent elbow injuries. Vasudevan et al. (2016) suggested that exercises such as Turning Point 4.0 partially replicate the muscular sequences of the swing and may be used for functional training and preventive rehabilitation.

2.3.1.5. Physical and neuromuscular factors

Performance in the golf swing depends not only on intersegmental coordination, but above all on the physical and neuromuscular capacities that support stability, strength, and motor control. Brožka et al. (2023) observed that greater jump power and maximum force moment of the knee extensors are positively correlated with CHS in young players. Johansen et al. (2023) confirmed that higher isometric strength and neuromuscular power are associated with higher swing speeds. Kim et al. (2019) demonstrated that eight weeks of strength training improve body composition, one-repetition maximum, 1RM, and drive distance. Lee et al. (2023) identified that isometric trunk rotational strength and extensor strength are the variables most strongly correlated with shot distance.

Sell et al. (2007) found that players with lower handicaps present greater strength in the trunk, shoulders, and hips, as well as better flexibility and balance, confirming that these physical capacities are determinants of an efficient swing. Marta et al. (2016) observed

that the greatest muscle activation occurs during the forward swing phase, especially in the hamstrings and biceps femoris, and that longer clubs increase muscular demand. Gulgin et al. (2009) reported that internal rotation of the lead hip is more pronounced than external rotation of the trail hip, suggesting that mobility of the lead hip plays a particularly relevant role in generating power during the downswing.

Farber et al. (2009) showed differences between skill levels, with professional players activating the pronator teres muscle of the lead upper limb during acceleration, whereas amateur players activate the trail upper limb. Zou and MacFarlane (2024) demonstrated that lower biceps/triceps strength ratios are associated with greater consistency at the impact point and longer distances. Triceps strength, dominant in the lead upper limb, correlated with more centered impacts and lower technical variation, suggesting that strength balance is determinant for club control.

Verikas et al. (2016) and Ebashi and Shibayama (1981) highlighted that professional players exhibit synchronized activation peaks at impact, unlike amateurs, who show dispersed patterns. Morrison et al. (2016) observed that experienced players display greater motor synergy in clubhead orientation, reinforcing that control of degrees of freedom is more important than a more rigid technique.

Suwondit et al. (2022) demonstrated that core strength and power are strongly correlated with pelvis and hip biomechanics, reinforcing that central stability is determinant for postural control. McNitt-Gray et al. (2013b) found that regulation of the horizontal forces exerted on the target-side foot influences muscular coordination, and Jones et al. (2024) reported that experienced players show lower variability in ground reaction forces, reflecting greater motor consistency.

Lim et al. (2012) and Marta et al. (2016) indicated that high compressive loads on the spine and greater activation of lower-limb muscles during powerful swings require core strengthening and muscular balance. Zemková et al. (2019) and Gryc et al. (2023) highlighted that asymmetric development of rotational power may contribute to functional imbalances, requiring continuous monitoring.

Bechler et al. (1995) and Jobe et al. (1986) emphasized the importance of coordination between hip and shoulder muscles, showing that pelvic stabilization and synchronized activation of the subscapularis and pectoralis major are fundamental during the acceleration phase. Wang et al. (2015) demonstrated that vertical reaction force in the lead lower-limb foot and contraction of the latissimus dorsi are positively associated with impact accuracy.

Rusdiana et al. (2021) and Chu et al. (2010) showed that the coordinated sequence of movements of the hip, trunk, and upper limbs is essential to generate power and accuracy. Kim and So (2017) reinforced that support-knee stability is determinant during weight transfer, whereas Han et al. (2019) and Horan and Kavanagh (2012) emphasized that trunk-pelvis coupling reduces motor variability, promoting greater kinematic consistency and movement control.

Mitchell et al. (2003), Horan et al. (2011; 2010), and Zheng et al. (2008) observed biomechanical differences between sexes and ages: men show higher angular velocities and pelvic rotation, whereas women and seniors show greater variability and lower range of motion, requiring adapted training approaches. Bourgain et al. (2020) reported high variability in joint moments during the downswing in a professional female player, indicating that motor control may be highly individual.

Vasudevan et al. (2016) showed that specific exercises, such as the Turning Point 4.0 Rotational Platform, partially replicate the muscular sequences of the swing and may be applied in gesture-specific training. Kim and Park (2020) used inertial measurement units, IMUs, and neural networks to segment swing phases with high precision, and Fossati et al. (2010) developed an accessible and reliable 3D motion capture system.

2.3.1.6. Methodology and technology applied to the study of the swing

Methodological and technological advances have played a decisive role in understanding the biomechanics of the golf swing, enabling more rigorous, personalized analyses that are closer to real playing conditions. The integration of three-dimensional motion capture, inertial sensors, and computational modeling has made it possible to precisely quantify the kinematic and dynamic variables that characterize this complex movement.

Smith et al. (2016) demonstrated that three-dimensional, 3D, analysis largely outperforms two-dimensional, 2D, analysis by eliminating projection errors and providing more reliable measurements of trunk flexion and lateral bending. Joyce et al. (2010) reinforced the importance of the Z-Y-X rotation sequence, lateral rotation, flexion-extension, and axial rotation, for assessing the X-factor and lower trunk movements, ensuring greater consistency between studies. Turner et al. (2020a) highlighted the need to standardize marker placement, especially when measuring axial wrist rotation, in order to reduce variability between investigations.

van der Walt and Baron (2024) tested the placement of inertial measurement units, IMUs, across the body and identified the lumbar region and wrist as the most reliable sensor

locations, showing high correlation with the actual movement of the club. This positioning optimizes low-cost portable measurements for analyses outside the laboratory.

Brown et al. (2013) and Y. H. Kwon et al. (2013) showed that different methods for calculating the X-factor produce significantly different values, underlining the importance of standardizing analysis protocols. Caldwell and McPhee (2024) developed and validated five three-dimensional models of club-ball impact, concluding that the adjusted impulse-momentum model offers the best balance between accuracy and computational efficiency. These models make it possible to optimize club design and fitting based on realistic biomechanical simulation.

Marsan et al. (2019) tested several methods for identifying the kinematic sequence of the swing and concluded that none is universally superior, arguing that the choice should be adapted to the player's characteristics and to the objective of the study.

Mahadas et al. (2019) applied computational simulations using OpenSim software to analyze swing dynamics in players of different levels, finding that the timing of the downswing transition is determinant for maximizing impact velocity. Lee and Park (2018) validated a multisegment mechanical model that estimates unmeasured variables from joint force moments, demonstrating high precision and consistency in the swing plane. Balzerson et al. (2016) developed a dynamic three-dimensional model that identified club shaft flexibility and optimal joint force moments as key factors for maximizing ball travel distance.

Kim et al. (2024) integrated biomechanical analysis and Laban Movement Analysis to map swing fluidity, showing that experienced female players exhibit more continuous instantaneous axes of rotation and better alignment with the club's inertia tensor. The choreographic approach provides a qualitative perspective that complements the coordination between the spatial orientation of movement and the management of inertial forces, as well as body awareness in technical training.

Brown et al. (2020) used an optimized biomechanical model that demonstrated the relevance of intersegmental timing and sequential force moments in determining final club velocity, validating the relationship between efficient coordination and lower mechanical demand. Zhou et al. (2022) proposed the Swing Performance Index, SPI, as a single score of rotational technique, built from three kinematic variables: pelvic rotational velocity before impact, pelvic rotational velocity at impact, and peak upper-trunk rotational velocity after impact. These metrics, extracted from 3D analysis, were

normalized and combined using principal component analysis and leave-one-out logistic regression to classify professionals versus amateurs, achieving an area under the curve, AUC, of 0.97. The index was scaled to a mean of 100 ± 10 in professionals and 82 ± 4 in amateurs, and also highlighted the relevance of the post-impact/follow-through phase as a performance indicator. The authors suggest using the Swing Performance Index, SPI, for rapid technical feedback and progress monitoring, while acknowledging the small sample size and the need for external validation across different devices and situations.

Kim and Park (2020) introduced artificial intelligence algorithms based on neural networks, BLSTM and CNN, applied to inertial measurement units, IMUs, enabling automatic segmentation of the swing phases with greater accuracy and efficiency compared with traditional methods. In a complementary way, Farnoosh and Ostadabbas (2022) demonstrated that artificial intelligence models are capable of identifying consistent backswing and downswing patterns, enabling automated movement analysis and its application to technical training.

Fossati et al. (2010) developed a 3D motion capture system using a single camera, which reconstructs complex gestures with high precision, making biomechanical analysis more accessible outside the laboratory context. O'Brien et al. (2020) compared optimized trajectories of the clubhead and the club's point of rotation, hub, both in the laboratory and in the field, showing that it is possible to improve impact velocity while respecting individual kinematic constraints.

Kanwar et al. (2021) evaluated the Minimalist Golf Swing, MGS, method and observed significant reductions in range of motion and in joint moments of the spine, hip, and knee. Although these changes reduce joint stress, they also observed reductions in club velocity and trajectory, highlighting the need to balance biomechanical protection and performance. Bairan Li et al. (2023) showed that variations in terrain slope restrict center-of-gravity movement and reduce muscle activation, demonstrating the need for postural adaptation to external conditions. Yang et al. (2024) demonstrated that lighter shafts increase clubhead speed and total distance, especially in low-handicap players, without significantly altering swing mechanics. In contrast, less experienced players showed greater displacement of the center of gravity, reflecting poorer postural control.

The integrated analysis of the literature reveals that the golf swing is a highly coordinated movement, in which efficiency depends on the harmonious interaction between kinematic, dynamic, and neuromuscular factors. The proximal-distal sequence of intersegmental energy transfer, pelvis-trunk coupling, and control of the base of support

constitute the biomechanical pillars of effective execution. Experienced players are characterized by more synchronized pelvic and thoracic rotation, predictable application of ground reaction forces, and a superior ability to modulate intersegmental timing.

The evidence shows that swing power results not only from isolated strength, but from coordination between body segments and central stability. Postural control, trunk rotational force moment, and core stability are determinant for velocity generation and for the protection of the spine and joints. Controlled variability of the swing plane and club trajectory, associated with a consistent hub path pattern, distinguishes elite players, while differences according to sex, age, and maturation highlight specific adaptations that should be considered in training.

In the neuromuscular domain, studies converge on the importance of muscular synergy and temporal synchronization of activation, with more concentrated patterns at impact among professionals. Compressive and shear forces in the spine, knee adduction moments, and rotational asymmetries highlight the need for mitigation strategies, such as strengthening the hip and trunk extensors, stability training, and optimization of the torque sequence.

On the other hand, methodological evolution, through the use of three-dimensional analysis, inertial sensors, computational modeling, and artificial intelligence algorithms, has increased the rigor and practical applicability of research. These tools allow movement to be assessed with greater fidelity and under more ecological conditions, provide immediate feedback, and personalize training according to the individual characteristics of the player.

Table 2.1. Characteristics of the selected studies addressing biomechanical analysis of the golf swing.

Study author	Sample	Procedure	Results
Alderslade et al. (2015)	7 experienced male golfers, aged 18-40 years	Passive hip range of motion, ROM, measurements were collected using a handheld inclinometer. Hip rotation data were captured with a 3D motion capture system during the golf swing.	There was a positive but non-significant correlation between passive ROM and dynamic ROM of the lead hip during the golf swing. There was a non-significant negative correlation between passive hip ROM and dynamic ROM during the golf swing of the lead hip. Improving passive hip ROM may not be associated with increased hip rotation used during the golf swing.
Balzerson et al. (2016)	Three-dimensional dynamic model of a golfer and club, including several biomechanical variables.	A swing simulation model was built, incorporating a golf model with 4 degrees of freedom, force moment generated by parameterized joints, a flexible shaft based on Rayleigh beam theory, and a ball impact and trajectory model. The simulations optimized the swing to maximize ball distance.	The model produced a carry distance of 195.7 m, 214 yards, with a ball speed of 60.8 m/s, 136 mph, and a launch angle of 18.1°. The simulation showed that shaft flexibility and optimal joint force moments improve swing performance. The resulting trajectory was validated with experimental data, showing a difference of only 3.23 m in mean distance.
Back et al. (2013)	14 professional golfers, mean age = 29 years, mean career length = 8.2 years	Analysis of the linear velocities of the center of mass, CoM, of the upper trunk and pelvis during the downswing. Six infrared cameras and SB-Clinic software were used to collect marker trajectories. The peak CoM velocity and the time at which each peak occurred were calculated.	A high coupling force between the upper trunk and pelvis was observed, with a mean correlation coefficient of $r = 0.86$. Coupling between segments was higher than within segments. High coupling may reduce motor control demands on the central nervous system and maintain consistent movement patterns.

Table 2.1. Continued

Study author	Sample	Procedure	Results
Baek et al. (2025)	55 male professional golfers, mean age 31 years and mean clubhead speed of 49.8 m/s.	3D kinematic study based on data from the TWU Golf Swing Analysis Database. Two trunk rotation sequences in the swing were compared: the conventional RBSB, rotation-flexion-side bending, ZXY sequence, and the new LDLR, directional lean-lean-rotation, ZXZ sequence. Thorax movement was recorded using markers placed on specific anatomical points and analyzed for angular interdependence, cross-talk, and range of motion.	The LDLR method showed less interference between angles and a greater range of primary rotation, 139° versus 120° in RBSB. The conventional RBSB method showed high correlation values between angles, revealing distortions in flexion and side-bending movements. The LDLR model was concluded to describe the axial movement of the thorax during the swing more accurately and realistically, reducing numerical errors and improving postural feedback in biomechanical analyses.
Bechler et al. (1995)	16 competitive golfers	Intramuscular electrodes and high-speed cinematography were used to record the electrical activity of the hip and knee muscles during the golf swing. EMG was synchronized with film to identify five phases of the swing.	The extensors and abductors of the trail hip, together with the adductor magnus of the lead hip, initiated pelvic rotation during the swing. The lead hamstrings kept the knee flexed and provided a stable base for pelvic rotation. Maximum muscle activity was recorded earlier than in previous studies of the trunk and shoulders, confirming the sequential firing pattern of the hip and knee muscles.
Betzler et al. (2012)	20 golfers	Analysis of the impact of club shaft stiffness on wrist kinematics and club presentation to the ball. Optical motion capture systems and radar were used to measure ball speed, launch angle, and spin.	Shaft stiffness had a marginal effect on club and ball speed, with increases of 0.45% and 0.7%, respectively, for the less stiff club. Main factors included faster recovery of the less flexible club and an increase in wrist angular velocity. Shaft bending was greater with lower

Table 2.1. Continued

Study author	Sample	Procedure	Results
			stiffness, and lead bending at impact increased marginally with the stiffer shaft. Changes in shaft stiffness had no significant effect on the measured parameters.
Bourgain et al. (2017)	3 recreational golfers, handicaps 19.5, 12, and 7, and 3 professional golfers, with 2, 5, and 9 years of experience. All were right-handed.	Participants performed 20 swings with their own drivers. A launch monitor, TrackMan 3, was used to measure ball trajectory. Ground reaction forces were recorded using two force platforms. Movement was captured by 12 cameras and 88 reflective markers, and the center of mass was calculated through multisegment kinematic optimization with OpenSim software.	Maximum global motor force moment was positively correlated with clubhead speed at impact. Vertical forces played a key role in generating global motor force moment, but horizontal forces were also decisive. Mean downswing duration was 0.27 s. Global motor force moment peaked before impact and was mainly generated by the vertical force of the lead foot and the horizontal force of the trail foot.
Bourgain et al. (2020)	1 female professional golfer	Motion capture with 12 cameras, force platforms to measure ground reaction forces, and radar.	Club speed ranged from 44.7 to 46.3 m/s; downswing duration was 0.28 s. Greater variability was observed in motor force moment.
Bradshaw et al. (2009)	20 golfers, 10 high-handicap and 10 low-handicap	Video analysis of 10 swings with a 5-iron to measure two-dimensional kinematic variables. Movement variability was quantified using the intraindividual coefficient of variation after correction for the standard error of measurement.	Absolute invariance in key technical positions, for example at the top of the backswing, appears to be a more favorable technique for skilled performance.
Brown et al. (2013)	19 male golfers	Analysis of the X-factor during the golf swing using a 12-camera 3D motion capture system. Three X-factor calculation methods were compared to determine	Significant differences were found between X-factor calculation methods at different phases of the swing.

Table 2.1. Continued

Study author	Sample	Procedure	Results
		similarities or differences between the data generated by each method. A 3D biomechanical model was created for each participant.	Regression analysis indicated that the methods were associated, although with interindividual variability.
Brown et al. (2020)	Biomechanical model with 4 degrees of freedom, DoF, flexible-shaft club, and optimized parameters for an average golfer, height: 1.74 m; mass: 73 kg.	Optimized dynamic model using direct collocation, GPOPS-II, to maximize ball flight distance. It included realistic biomechanical constraints, such as joint torque limits, club deflection in two planes, and aerodynamic parameters of ball flight. The movement was optimized to generate ideal force moments in the torso, shoulder, forearm, and wrist.	The model optimized force moment profiles, resulting in final club speed of 46.7 m/s and ball speed of 68.6 m/s, maximizing carry distance. The study highlighted the importance of timing and sequential activations, with force moments stabilizing the club during the backswing-to-downswing transition.
Brožka et al. (2023)	19 experienced male junior golfers	Two-year longitudinal study assessing the relationship between body composition, lower-limb physical characteristics, and clubhead speed, CHS. Parameters such as height, lean mass, jump power, countermovement jump and squat jump, and maximum force moment of the knee extensors at $60^{\circ} \cdot s^{-1}$ were analyzed.	There was a significant positive relationship between increased CHS and growth in height, maximum countermovement jump power, and squat jump power. The relationships between increased CHS and increased lean mass, $r = 0.42$; $P = 0.06$, and maximum force moment of the knee extensors, $r = 0.44$; $P = 0.07$, were nearly significant.
Bulbulian et al. (2001)	7 golfers, 6 male and 1 female, aged 26.5 ± 3 years	Bilateral electromyography, EMG, recordings of the lumbar, external oblique, latissimus dorsi, and pectoral muscles on the dominant and non-dominant sides during a full swing and a reduced-backswing swing. High-speed video was used to measure the reduction in backswing	Reducing the backswing by 46.5 ± 24.7 degrees did not affect shot accuracy or significantly reduce CHV, 33.9 ± 2.5 m/s versus 31.2 ± 2.2 m/s. Dominant-side oblique activation decreased by 19% from 750 to 250 ms before impact. Non-dominant-side lumbar muscle activation decreased by 12%, while dominant-side latissimus dorsi

Table 2.1. Continued

Study author	Sample	Procedure	Results
		angle. Clubhead velocity, CHV, and ball contact accuracy were quantified.	activation increased by 21% during the acceleration phase. Non-dominant-side lumbar activation increased by 14% during the follow-through. There was an overall trend toward increased shoulder muscle activation.
Burden et al. (1998)	8 golfers with sub-10 handicap	Analysis of the swing of sub-10 handicap golfers using 3D techniques to capture the movement of the shoulders, upper limbs, and club.	During the backswing, the shoulders rotated more than 90°. In 75% of players, shoulder rotation continued away from the target line while the hips began rotating toward the target. This sequential hip-shoulder rotation pattern confirmed the principle of summation of velocities, according to which the progressive increase in proximal rotation generates greater force moment, torque, in the club before impact. Drive speed was also favored by displacement of the center of mass predominantly toward the target, supporting the intended ball trajectory at impact.
Caldwell and McPhee (2024)	56 elite players, scratch level or better, who performed 550 drives and 120 shots with a 7-iron.	Computational modeling and experimental validation study. Five 3D club-ball impact models were developed based on two main approaches: impulse-momentum and continuous contact. The models were tested for drivers and irons, 7-iron, using real data collected with a Vicon system and GC2 launch monitor. Calibration was performed through hybrid regression, combining a genetic algorithm	The adjusted impulse-momentum model was the most accurate for drivers, with mean error below 1% for ball speed and below 10% for launch angles and backspin. The two-layer volumetric model was the most effective for the 7-iron, with only 2% error in ball speed. The impulse-momentum models had 100-fold lower computational time, making them ideal for club design

Table 2.1. Continued

Study author	Sample	Procedure	Results
		and fmincon optimization, to minimize error between simulated and measured values.	and fitting applications due to their high accuracy and efficiency.
Chaemkhan et al. (2025)	30 amateur players, 15 men and 15 women, handicap between 0 and 15, right-handed and without recent musculoskeletal injuries.	Experimental study with 3D kinematic and kinetic analysis of the golf swing. Instrumented insoles, Surasole Pro 8, and two force platforms synchronized with a 3D motion capture system, Qualisys, 200 Hz, were used. Trunk energy flow was calculated at L5-S1, and stepwise multiple linear regression was applied to identify the plantar regions that best predicted energy transfer.	Peak pressures occurred in the medial metatarsus of the trail foot and in the lateral arch of the lead foot, both positively associated with trunk energy transfer. In contrast, excessive pressure on the hallux of the lead foot showed a significant negative correlation. The model explained about 80% of the variability in energy transfer. It was concluded that balanced plantar distribution favors efficient energy transfer from the ground to the trunk, while asymmetric patterns compromise efficiency and increase the risk of lumbar overload.
Chen et al. (2024)	21 right-handed highly skilled players, 9 men and 12 women, aged 18-30 years, mean handicap 2.4.	Performance in the overhead squat test, OHS, was assessed according to the FMS protocol, dividing participants into High-Scoring, HS, and Low-Scoring, LS, groups. The driver swing was analyzed with high-speed cameras, 250 Hz, and force platforms, 1000 Hz. A 3D musculoskeletal model, OpenSim 4.3, was used to estimate lumbar joint forces, L1-S1, with kinematic, electromyographic, and force data collection.	The HS group showed greater lumbar extension range of motion and lower angular velocity, indicating more efficient trunk control during the downswing. Shear forces at L4-L5 and L5-S1 were significantly lower in the HS group, although compressive forces did not differ. Better OHS performance was concluded to be associated with greater lumbar stability and lower risk of vertebral overload, making it a useful functional indicator for predicting load patterns and low back pain risk in golfers.

Table 2.1. Continued

Study author	Sample	Procedure	Results
Cheng et al. (2025)	84 elite male golfers, professionals, university players, and teaching pros, all right-handed, with handicap ≤ 3 and clubhead speed above 100 mph.	Cross-sectional observational study based on the Texas Woman's University Golf Swing Database. Each participant performed seven maximal drives with their own driver, recorded with 10 Qualisys cameras, 500 Hz, and 65 markers. Four wrist-release styles were identified: Delayed Release 1, DR1, Delayed Release 2, DR2, Early Release, ER, and Recocking, RC. Kinematic analysis included angular velocities, phase durations, and in-plane and out-of-plane swing deviations.	The DR1 style showed higher wrist uncocking velocity and a more inclined and open movement plane, with complete proximal-distal transition. RC showed a longer downswing and shorter transition, while ER showed greater clubhead separation and a weaker segmental sequence. Mean clubhead speed was similar across styles, around 49.7 m/s. The DR1 pattern was concluded to be the most efficient, combining body-guided backswing, delayed release, and sequential transition, while ER and RC reflect more upper-limb-dominated and less efficient patterns.
Choi et al. (2016)	21 right-handed professional golfers	Infrared cameras were installed to capture swing motion. Axial rotation angle, angular velocity, and interarticular coordination were calculated using Euler angles, numerical differentiation, and continuous relative phase, respectively.	The most typical interarticular coordination was observed in the lead hip/trunk compared with the trail hip/trunk. Three lead hip/trunk coordination characteristics showed a significant relationship with clubhead speed at impact in male professional golfers. Increased rotation difference between the lead hip and trunk during the overall downswing phase, as well as faster lead hip rotation compared with the trunk early in the downswing, play important roles in increasing clubhead speed.
Choi et al. (2014)	20 professional golfers, registered with the Korea	Kinematic assessment of movement smoothness during the downswing, using six infrared cameras, VICON460	Experienced players showed smoother movements during the downswing than amateurs. Smoothness of

Table 2.1. Continued

Study author	Sample	Procedure	Results
	Professional Golf Association, and 19 amateur golfers	system, to capture the three-dimensional trajectory of markers placed on body segments and the golf club. Smoothness was assessed using the jerk index, which represents the change in acceleration over time.	lower-limb joints was positively correlated with smoothness of clubhead trajectory, suggesting that control of the lower joints is determinant for executing a fluid swing.
Chu et al. (2010)	308 golfers	Data from 308 golfers were analyzed, focusing on swing kinematic variables and ground reaction forces to identify important variables for ball speed.	Torso-pelvis separation, X-factor, delayed release of the upper limbs and wrists, forward and lateral trunk tilt, and weight displacement during the swing were significantly related to ball speed.
Coleman and Anderson (2007)	10 male golfers with a mean age of 20.1 years, handicap 1-5	Participants performed repeated and consistent swings with three different clubs, driver, 5-iron, and pitching wedge. The movement of each club during the downswing was fitted to a single plane to assess swing plane fit and variation.	Swing plane fit varied significantly between players and between different clubs. Mean plane angles relative to the horizontal reference axis and to the target-line axis showed statistically significant differences.
Coleman and Rankin (2005)	7 right-handed golfers of different skill levels, handicap 0-15.	Three-dimensional kinematic analysis to define the left upper-limb plane, delimited by the seventh cervical vertebra, the left shoulder, and the left wrist. The angles of this plane relative to the vertical axis, z, and the target line, anteroposterior axis, were measured during the downswing.	The plane angle relative to the z axis, vertical, varied from $133^{\circ} \pm 1^{\circ}$ at the start of the downswing to $102^{\circ} \pm 4^{\circ}$ at impact, indicating increased inclination of the left upper-limb plane. The angle relative to the target line changed from $-9^{\circ} \pm 16^{\circ}$ to $5^{\circ} \pm 15^{\circ}$, showing progressive rotation of the upper-limb plane toward the target. The distance between the clubhead and the left upper-limb plane varied from $0.019 \text{ m} \pm 0.280 \text{ m}$ at the start of the downswing to $0.291 \text{ m} \pm 0.077 \text{ m}$ at impact. These results indicate that the left upper limb and shoulder

Table 2.1. Continued

Study author	Sample	Procedure	Results
			girdle do not move in a fixed plane, and that the club does not rigidly follow that plane.
Dale and Brumitt (2016)	13 experienced male golfers	Biomechanical comparison between full and shortened modern, one-plane, swings. Kinematic data of the X-factor, spinal forces, and performance variables were analyzed, including clubhead velocity, CHV, shot distance, and accuracy. Each player performed 10 swings with their 7-iron.	The shortened swing significantly reduced the X-factor and vertebral compression force, and also resulted in reduced CHV, about 2 m/s, and shot distance, about 10 m. The shortened swing may reduce spinal stress, but negatively affects performance.
D’Arcy et al. (2021)	28 recreational amateur golfers, 17 men and 11 women, mean age 47 years, handicap between -3 and -36, mean = -15.	The effects of five grip positions, from +30° to -30° in 15° increments, on drive accuracy and distance were analyzed. Data were collected with TrackMan™, and golfers performed 9 trials with each grip after a standardized warm-up.	Stronger grips, -15° and -30°, improved accuracy and distance. Weaker grips, +15° and +30°, showed greater lateral deviations, reduced clubhead speed, and shorter distance. Neutral, 0°, and strong grips showed comparable results. Weak grips produced significantly poorer performance. Adaptation between trials was observed, but without evident fatigue.
Dong and Ikuno (2023)	1 intermediate golfer, 1 single-handicap golfer, and 3 beginner golfers	Biomechanical analysis of golf swing movements using an accessible inertial motion capture system and the Hilbert-Huang Transform, HHT, to analyze instantaneous frequency and amplitude. Comparison between straight and slice swing trajectories.	Differences were found between straight and slice swings at impact. For the intermediate player, increased amplitude of head and non-dominant lower-limb movements was associated with a slice trajectory. For the single-handicap player, hip and non-dominant upper-limb movements were identified as the main contributors to the slice pattern. In beginners, patterns varied between

Table 2.1. Continued

Study author	Sample	Procedure	Results
			trials, indicating greater motor variability and lower swing stability.
Ebashi (1981)	3 professional golfers and 4 amateurs	Analysis of the golf swing using EMG for involved muscles and high-speed cinematography to study kinematic characteristics of movement.	In professional players, muscle activities were more synchronized and concentrated at impact. Professionals showed higher clubhead speed, 63.31 m/s, and ball speed, 67.65 m/s. Amateurs displayed less synchronized muscle activation patterns, longer swing time, and lower clubhead speed, 52.00 m/s, and ball speed, 62.86 m/s. Amateurs also showed greater impulse and a significant correlation between initial ball speed and clubhead speed.
Egret et al. (2003)	7 right-handed male golfers, aged 17-34 years	The kinematic pattern of the swing was assessed with three different clubs, driver, 5-iron, and pitching wedge. Kinematic data were collected with the VICON optoelectronic system, and club speed was measured with a swing detector.	The coordination pattern of body segments was similar across the three clubs, although kinematics and club speed varied according to the type of club used.
Fan et al. (2025)	13 right-handed male golfers, regular fitness practitioners, mean age 21 years, without upper-limb injuries.	Cross-sectional experimental study comparing five push-up variations: standard, wide grip, narrow grip, internal rotation, and external rotation. Electromyographic activity of ten upper-limb muscles was recorded with Delsys Trigno sensors, 1200 Hz, synchronized with 3D motion capture. Muscle synergy analysis was performed using non-negative matrix factorization.	All variations were explained by two main muscle synergies. The wide grip increased posterior deltoid activation and reduced pectoralis major activation; the narrow grip intensified triceps and upper trapezius activation; internal rotation increased serratus anterior activation; and external rotation reduced forearm muscle activation but increased biceps and upper trapezius

Table 2.1. Continued

Study author	Sample	Procedure	Results
			activation. Differences emerged mainly in the eccentric phase, indicating that control during this phase may optimize the neuromuscular effects of each variation.
Farber et al. (2009)	10 amateur golfers and 10 professional golfers, all right-handed	Fine-wire electromyography was used to measure activity in the flexor carpi radialis, pronator teres, flexor carpi ulnaris, and extensor carpi radialis brevis muscles of both forearms. EMG data were synchronized with video, and muscle activity was expressed as a percentage of maximum voluntary isometric contraction, MVIC, for each muscle.	Amateur golfers showed more activity in the pronator teres of the trail upper limb, right arm in a right-handed golfer, during the forward swing phase and a tendency toward more activity during acceleration. Professional golfers showed more activity in the pronator teres of the lead upper limb, left arm in a right-handed golfer, during acceleration and a tendency toward more activity in the early follow-through phase.
Farnoosh and Ostadabbas (2022)	3D motion capture data from four activities: bat flight, salsa dancing, walking, and golf swing.	A deep generative dynamic model was used to segment motion data into interpretable latent states. Data were analyzed in a reduced-dimensional space based on an autoregressive model with dynamic transition.	The model outperformed existing methods in motion segmentation and generation, capturing interpretable dynamic states in each activity. In the case of golf, movements were divided into main phases, such as backswing and downswing, allowing a clearer understanding of swing dynamics. The approach showed superior accuracy in predicting and segmenting complex motion data.
Fossati et al. (2010)	Golfers and walkers, number not specified, performing golf swings and walking	Development of a 3D motion capture system using only one camera. It combines detection of characteristic postures with interpolation and refinement using	The system was able to reconstruct 3D golf swing movements with high accuracy, even with a single camera. The combination of posture detection and

Table 2.1. Continued

Study author	Sample	Procedure	Results
		generative models. Applied to golf swings filmed with a static camera.	tracking reduced prediction errors and allowed complex movements to be captured robustly.
Frontani et al. (2022)	18 right-handed golfers divided into 3 groups, 4 professionals, 5 intermediates, and 9 beginners	Analysis of knee biomechanics during the golf swing under ecological conditions. Acceleration of the support-side knee was measured with a Shimmer3 triaxial sensor, and ZeppGolf was used to select each player's best shot. Oscillatory differences were compared across three player groups according to handicap.	Professional players showed greater knee acceleration compared with intermediate and beginner players, especially at frequencies of 1-2 Hz and 2-3 Hz. Intermediate players presented irregular movements with large acceleration and deceleration variations. Beginner players showed smoother movement, but with limited range of motion.
Fuyu et al. (2019)	7 elite golfers and 13 intermediate golfers	Motion capture with a VICON system. Analysis of positional club control and clubface orientation during impact.	Significant differences between groups were found in standard deviations of shaft location, minimum distance between the center of the sweet spot and the ball at impact, elevation angle, EA, and azimuthal angle, AA. Elite players showed more convergent turning point locations, shorter distances between the sweet spot and the ball at impact, higher EAs, and lower AAs.
Gould et al. (2021)	62 golfers, 40 boys and 22 girls, mean age 15.4 ± 2.4 years	Assessment of movement capabilities using a golf movement screen, GMS, across 10 exercises. Biomechanical data were collected using an electromagnetic tracking system during the backswing and impact.	Four of the 10 exercises showed significant correlation with the X-factor. Spinal control correlated with 9 of the 10 exercises and with total GMS score. Golfers with better GMS scores showed better spinal control and higher X-factor.

Table 2.1. Continued

Study author	Sample	Procedure	Results
Gryc et al. (2023)	8 girls, 15.4 ± 1.0 years, and 6 boys, 15.8 ± 1.7 years	Performance of 10 driver swings under laboratory conditions. Measurement with a 3D motion capture system.	Significant differences in maximum pelvis and thorax rotations were found between boys and girls. In boys, there was a significant negative relationship between maximum thorax rotation, X-factor, and club speed. In girls, there was no significant relationship between movement parameters and club speed.
Gulgin et al. (2009)	15 female collegiate golfers	High-speed 3D motion capture with a bilateral multisegment marker set during multiple repetitions of a drive.	Internal rotational velocity of the lead hip was significantly greater than external rotational velocity of the trail hip. The lead hip is subjected to higher rotational velocities during the downswing compared with the trail hip.
Gulgin et al. (2010)	15 right-handed female collegiate golfers, mean age 19.6 years; mean handicap 5.2.	Internal and external hip rotation range of motion, ROM, was assessed under three weight-bearing, WB, conditions and during full golf swings using a 3D motion capture system. Asymmetries between the lead hip and trail hip were analyzed.	The lead hip showed greater internal and external rotation during swings, highlighting an asymmetric movement pattern. Players used up to 131% of the available internal ROM of the lead hip under certain conditions, suggesting that fatigue or inadequate posture may increase injury risk. Functional WB ROM assessment is recommended to prevent problems.
Han et al. (2019)	64 experienced male golfers, handicap ≤ 3	Swing trials were captured using an optoelectronic system. Angular positions and velocities in the functional swing plane, FSP, were calculated.	Backswing and transition sequences were consistent between groups, showing complete or partial proximal-distal sequences with minor variations. The downswing sequence was inconsistent, with peak angular velocities

Table 2.1. Continued

Study author	Sample	Procedure	Results
			of body segments not significantly separated. Separation styles influenced swing characteristics.
Han et al. (2019)	63 highly experienced golfers, handicap ≤ 3	Shots were performed under 3 club conditions, driver, 5-iron, and pitching wedge, captured using an optoelectronic motion capture system and 2 force platforms.	Two main force moments were identified: the moment resulting from ground reaction forces in the front-back axis and the pivot moment around the vertical axis. Significant correlations were found between force parameters, force moment peaks, and clubhead speed. The lead foot contributed mainly to the moment resulting from ground reaction forces, while the trail foot contributed more to the pivot moment. Loading on the lead foot at the instant when the lead upper limb becomes parallel to the ground was critical for generating maximum force moments.
Healy et al. (2011)	30 golfers divided into 2 groups based on ball launch speed, high: 52.9 ± 2.1 m/s; low: 39.9 ± 5.2 m/s	3D marker coordinate data, 250 Hz, were used to calculate joint kinematics at 8 key swing events. Swing analysis measured club swing characteristics and ball launch.	Significant differences between groups were observed for clubface impact point and several joint angles and angular velocities: greater shoulder flexion and lower internal rotation of the non-dominant upper-limb shoulder in the backswing, greater angular extension velocity in the shoulders at the start of the downswing, greater angular adduction velocity of the non-dominant upper-limb shoulder at ball contact, greater hip joint movement and X-factor during the downswing, and greater elbow extension of the non-dominant upper limb

Table 2.1. Continued

Study author	Sample	Procedure	Results
			at the start of the downswing contributed to greater distance with the 5-iron.
Hooker et al. (2018)	20 healthy participants	3D biomechanical analysis of participants performing three golf shots under different stance conditions: bilateral 0° foot angle, bilateral 30° foot angle, wide and narrow stance widths, and self-selected stance.	The 30° foot angle stance and wide stance significantly reduced the external knee adduction force moment of the lead lower limb compared with the self-selected stance, without affecting swing speed. Modifying stance can reduce knee loads without impairing performance.
Horan and Kavanagh (2012)	14 male professional golfers, mean age 27 ± 8 years, golf experience 13.3 ± 8 years.	3D data were collected using an optical motion analysis system. The magnitude and timing of peak angular velocity were determined for the head, thorax, and pelvis segments during the downswing.	The thorax segment showed the greatest peak velocity magnitudes in the upper body during the downswing. A strong coupling relationship was observed between the thorax and pelvis, while the head and thorax showed a much more variable relationship. Strong thorax-pelvis coupling may be a strategy to simplify motor control during the downswing and ensure consistent motor patterns.
Horan et al. (2010)	19 male and 19 female golfers	3D movement data were collected using an optoelectronic analysis system. Angular positions and velocities of the thorax and pelvis were measured.	Men showed greater posterior pelvic tilt, greater lateral tilt, and lower axial rotation compared with women. Men also showed higher angular velocity at impact.
Horan et al. (2011)	38 golfers, 19 men and 19 women	3D data were collected from the thoracic, pelvic, hand, and clubhead segments during the downswing phase of the full swing.	Female players showed greater variability in axial trunk and pelvic rotation at mid-downswing and at ball contact. Greater variability was found in thoracic-pelvic coupling among women. Variability in the hand and

Table 2.1. Continued

Study author	Sample	Procedure	Results
			clubhead trajectories decreased progressively from the top of the backswing to ball contact for both sexes.
Ichikawa et al. (2022)	14 amateur golfers and 14 experienced golfers	Fifteen drives, three sets of five shots, were analyzed for each participant using their own clubs in an indoor driving range. Data on clubhead movement at impact were collected using a Doppler monitor, FlightScope X3.	Experienced golfers showed consistently smaller face-to-target angles across all sets compared with amateur golfers, $p < 0.5$. Higher clubhead speed, CHS, correlated with mean number of shots, without compromising clubface control. Experienced golfers achieved extremely precise face control even at high club speeds.
Jobe et al. (1989)	6 male professional golfers, 35 ± 4 years; 30-42 years, and 7 female professional golfers, 32 ± 6 years; 24-44 years, all right-handed and with healthy shoulders.	Study of electromyographic activity of 8 shoulder muscles, pectoralis major, latissimus dorsi, supraspinatus, infraspinatus, subscapularis, anterior deltoid, middle deltoid, and posterior deltoid, using needle electromyography. The takeaway, forward swing, acceleration, and follow-through phases were analyzed.	Visual analysis indicated that women showed slightly higher activity during the takeaway and forward swing phases, while men showed higher activity during the acceleration and follow-through phases.
Jobe et al. (1986)	7 professional golfers, right-handed	Analysis of bilateral shoulder muscle activity during the golf swing using electromyography and high-speed video recording. Recordings were acquired at 450 fps, synchronized with electromyographic signals.	In the dominant upper limb, the deltoid remained inactive; the rotator cuff showed low-level activity in the supraspinatus and infraspinatus and greater activation of the subscapularis. In the non-dominant upper limb, the deltoid showed brief anterior activity before ball contact. The subscapularis was the most active during the swing. Latissimus dorsi and pectoralis major activity was notable during the acceleration phase. The idea that the

Table 2.1. Continued

Study author	Sample	Procedure	Results
			non-dominant upper limb provides more “drive” than the right arm was refuted.
Johansen et al. (2023)	21 national-level golfers, age: 21.9 ± 3.9 years; handicap: $+1.1 \pm 1.7$	Measurement of maximum isometric strength, MVC, in the mid-thigh pull and bench press; assessment of rate of force development, RFD, during leg press; trunk rotational power; countermovement jump, CMJ; and active range of motion, AROM, of the hip. Comparisons were made between players with high, FTG, and low, STG, clubhead speed, CHS.	CHS was positively correlated with isometric strength in the mid-thigh pull and bench press, RFD in the leg press, trunk rotational power, and CMJ parameters, except RFDdyn. The FTG group showed greater isometric strength, RFD, and trunk power, but lower hip range of motion compared with STG. Greater neuromuscular strength and power are associated with higher CHS, which may provide a competitive advantage.
Jones et al. (2021)	104 amateur golfers	Variability of ground reaction force during driver and 5-iron shots was analyzed using principal component analysis, PCA. Three components of ground reaction force were considered.	More experienced golfers showed significantly lower variability in 2 of 5 principal components with the driver and 4 of 5 principal components with the 5-iron. Lower intraindividual variability compared with interindividual variability was also observed, suggesting that experienced golfers maintain consistent ground reaction force patterns, which may explain lower variability in shot outcomes.
Joyce (2017)	15 low-handicap male golfers with a modern swing	Swing kinematic data were measured using a 10-camera motion analysis system, 250 Hz, and clubhead speed was collected using a validated launch monitor. Swings with a driver and a 5-iron were compared.	There were no differences in X-factor and Crunch between the driver and 5-iron. Correlation analyses revealed that segmental interactions, trunk and lower trunk, differed between the two clubs. A larger number of kinematic variables associated with the X-factor

Table 2.1. Continued

Study author	Sample	Procedure	Results
			correlated with higher clubhead speeds. The regression model with the 5-iron showed that higher clubhead speed is associated with increased X-factor stretch in the lower trunk and reduced lateral trunk flexion.
Joyce et al. (2016)	20 high-level amateur golfers, mean handicap = 1.9 ± 1.9	3D trunk and wrist kinematics were collected under two modified club conditions; a launch monitor was used to measure swing parameters and launch conditions.	Wrist kinematics was the variable most associated with clubhead speed, indicating the importance of the wrist in producing speed, regardless of club properties. Faster axial trunk rotation and earlier wrist release occurred mainly with shorter clubs, such as short irons.
Joyce et al. (2016)	35 high-level amateur golfers, mean age 23.8 ± 2.1 years; handicap 5 ± 1.9	3D motion analysis with 10 cameras, 500 Hz, to capture swing data; launch monitor to measure clubhead speed and launch angle.	A positive relationship was found between axial rotation of the trunk and lower trunk. Strong coupling between the trunk and lower part was observed in the crunch factor. Higher club speeds and lower launch angles were associated with lower lateral flexion of the lower trunk.
Joyce et al. (2010)	Three-part methodological study: models and algorithms; visual estimates; dynamic analysis of golf swings.	1) Development and validation of models and algorithms using a wooden model. 2) Comparison of visual estimates of 3D trunk posture with six Cardan rotation orders during representative moments of the golf swing. 3) Analysis of sequence dependency in real golf swings using 3D motion analysis.	The lateral bending/flexion-extension/axial rotation sequence, ZYX, was considered the most appropriate for evaluating the X-factor and lower trunk movement in the golf swing.
Kanwar et al. (2021)	15 right-handed golfers, 5 women and 10 men, aged 18-73	Participants' existing golf swing was compared with the Minimalist Golf Swing, MGS. Participants underwent biomechanical assessments and took part in 4 MGS	MGS reduced range of motion, ROM, of the lumbar spine, 18.3% in the transverse plane, hip, 40.7% in the sagittal plane and 41.8% in the frontal plane, and knee,

Table 2.1. Continued

Study author	Sample	Procedure	Results
	years, handicaps between +2 and -20.	training sessions. Data were collected with reflective markers placed on anatomical landmarks, force platforms, and an infrared-camera-based three-dimensional motion capture system, allowing assessment of joint angles and force moments in the lumbar spine, hip, and knee.	39.2% in the sagittal plane. Joint moments at the hip and knee were also reduced. Consequently, club speed decreased and club trajectory was modified.
Kao et al. (1995)	15 competitive golfers	Study of bilateral scapular muscle activity using electromyography and cinematography.	In the trail upper limb, the levator scapulae elevates and the rhomboids retract the scapula during the takeaway, stabilizing it throughout the rest of the swing. In the lead upper limb, these muscles retract the scapula during the forward swing and acceleration. The trapezius of the trail upper limb shows high activity during the takeaway, and in the lead upper limb, trapezius activity is high during the forward swing and the rest of the swing to promote scapular retraction. Serratus anterior activity is high in the trail upper limb during the forward swing and remains high throughout the rest of the swing, while in the lead upper limb, serratus activity is constant across all swing phases, which may explain muscle fatigue in golfers with higher effort intensity. Synchrony of the scapular muscles is fundamental for maximizing the swing arc and clubhead speed.

Table 2.1. Continued

Study author	Sample	Procedure	Results
Kawashima (1989)	14 male golfers	Measurement of finger grip forces in both hands and accelerations in two directions during the golf swing, using miniaturized force sensors and 16-mm high-speed cinematographic analysis.	Peak forces of the little, ring, and middle fingers of the left hand were significantly higher in elite players compared with beginners.
Khuyagbaatar et al. (2019)	10 low-handicap male golfers	3D motion capture system to obtain swing kinematics. Analysis of trail lower-limb knee variables, trail upper-limb shoulder external rotation, lead upper-limb elbow extension, lead lower-limb knee adduction, and lower-trunk tilt.	Variables such as trail lower-limb knee adduction, trail upper-limb shoulder external rotation, and lead upper-limb elbow extension were predictors of the X-factor. Pelvic movement was associated with joint angles during the backswing and with movement toward the target, with rotation toward the trail side, during the downswing and follow-through.
Kim and Park (2020)	9 professional and 11 amateur male golfers. All right-handed, mean age 41.2 years, mean height 175.4 cm, and mean weight 79.9 kg.	Data were collected from 20 participants using IMUs, inertial measurement units, placed on the wrist of the lead upper limb, head, and waist. Each participant performed 10 swings with a driver and 10 with a 7-iron. Signals were processed using deep learning algorithms, specifically BLSTM, Bidirectional Long Short-Term Memory, and CNN, Convolutional Neural Network, for automatic segmentation of swing phases.	BLSTM- and CNN-based methods showed higher accuracy in segmenting swing phases compared with the traditional heuristic method. Mean absolute error ranged from 5 to 92 ms. CNN showed slight superiority in computational efficiency, suggesting potential applications in automatic movement analysis in golf.
Kim and So (2017)	15 professional golfers and 10 amateurs	3D motion analysis of the knee during the downswing and assessment of muscle strength under isokinetic conditions, constant angular velocity, with driver and 5-iron clubs.	Professional golfers showed a smaller minimum angle in the lead knee; amateurs showed higher angular velocity in the lead knee with the 5-iron.

Table 2.1. Continued

Study author	Sample	Procedure	Results
Kim et al. (2019)	11 female professional golfers from the Korean Golf Association, with more than 30% body fat and without medical diseases	Eight-week combined training program focused on developing muscle strength. Body composition, one-repetition maximum, 1RM, muscle activity, and drive distance were assessed in week 1 and week 8. Exercises included hip adduction, lat pull-down, shoulder press, knee flexion, and knee extension.	After training, there was a significant reduction in body fat and increase in lean mass, $p < 0.001$. All 1RM measurements increased significantly, $p < 0.001$. Increased muscle power of the external oblique and latissimus dorsi, $p < 0.05$, as well as drive distance, $p < 0.05$, were also observed.
Kim et al. (2022)	20 professional golfers	Analysis of the effects of anteroposterior ball position, five different positions, on golf swing behavior. Data were collected using a 3D motion capture system and two force platforms.	More rearward ball positions were associated with more open joint angles of the trunk, knee, and ankle in the sagittal plane throughout the swing. These positions were also associated with reduced horizontal forces and lower values of pelvic rotation and X-factor in the transverse plane during the downswing. More forward ball positions showed opposite patterns, with less joint extension and greater pelvic rotation.
Kim et al. (2024)	Two female players: one novice, 17 years old, handicap 32, and one experienced player, 51 years old, handicap 8.	Exploratory study integrating Laban Movement Analysis, LMA, with biomechanics. Twelve Qualisys cameras, 300 Hz, and one Kistler force platform were used to capture the swing from the start of the downswing to before impact. Rotations were modeled using Screw Theory, 6 DoF, extracting instantaneous screw axes and the club inertia tensor, and mapping movement in the Kinesphere, icosahedron, and Laban Effort Cube.	The experienced player showed more continuous instantaneous axes aligned with the club's principal axes, reflecting greater movement efficiency and fluency. The novice showed greater discontinuity and inertial deviations. The integration of LMA, Screw Theory, and inertia tensor proved useful for relating movement qualities, Effort/Shape, with biomechanical metrics, offering an ecological approach to technical

Table 2.1. Continued

Study author	Sample	Procedure	Results
			training, injury prevention, and motor pattern rehabilitation.
Kwon et al. (2012)	14 experienced male golfers, mean handicap = -0.5 ± 2.0	Golf swing motion was captured with driver, 5-iron, and pitching wedge using an optical motion capture system, 250 Hz. The functional swing plane, FSP, of the clubhead and movement planes, MPs, of shoulder/upper-limb points were analyzed, including relative inclination and inclination direction.	FSP and MPs showed significant variations based on the club used. Experienced golfers showed semi-planar swings with two distinct stages: a transition phase and a planar execution phase. MPs of shoulder/upper-limb points showed large deviations from the FSP, highlighting that these points move in substantially different MPs.
Kwon et al. (2021)	66 skilled male golfers, handicap ≤ 3	Analysis of linear relationships between hand movement characteristics and clubhead movement during driver shots. Hand movement plane, HMP, angles, functional swing plane, FSP, differences between planes, planarity, and attack angles were calculated using an optical motion capture system.	Three main swing patterns were identified: 1) parallel HMP-FSP alignment, a planar pattern with small directional deviation; 2) internal alignment, flatter planes and downward/inward impact; and 3) external alignment, steeper planes and upward/outward impact. Training focused on the hand movement pattern can reprogram the overall swing pattern.
Kwon et al. (2013)	18 experienced golfers, handicap = -0.6 ± 2.1	Five driver trials were captured for each participant using a motion capture system, 250 Hz. Three methods were applied to calculate X-factor parameters: 1) conventional method; 2) method based on the functional swing plane; and 3) method based on Cardan rotation, three-dimensional angular calculation.	The X-factor calculation methods showed statistically significant differences from each other. The conventional method produced substantially higher values, and X-factor parameters did not correlate directly with maximum clubhead speed.

Table 2.1. Continued

Study author	Sample	Procedure	Results
Lamb et al. (2018)	16 low-handicap golfers, mean = 4.1	Analysis of pelvis-thorax coordination during swings with a 5-iron and 6-iron. Swings were performed under three effort conditions, minus, norm, plus, for both clubs, with 10 swings in each condition for each club, totaling 60 swings per participant.	No significant differences in X-factor were found between clubs or effort levels. However, X-factor stretch varied significantly according to club and swing intensity. Continuous relative phase, CRP, evidenced the stretch-shortening cycle during the downswing, more pronounced under higher effort conditions. Substantial interindividual variability suggests the need for further individual analyses to investigate pelvis-thorax coordination in the golf swing.
Langlais and Broker (2014)	8 low-handicap golfers, 0 to 7	Measurement of grip pressures during the swing with a 7-iron and a driver. Analysis of force variability and profile.	Large fluctuations in grip forces were observed during the swing, with marked differences between participants. Predominant forces came from the dominant hand, especially the last three fingers. Force profiles were highly repeatable between swings and between clubs, with high correlations. Within-swing force variability was greatest during club acceleration and decreased dramatically at impact.
Lee and Park (2018)	12 golfers of different skill levels	Golf swing data were collected with driver and 7-iron using a multisegment mechanical model to estimate unmeasured upper-limb movement data. 3D motion data were projected onto a 2D plane during the downswing to simplify dynamic analysis.	The proposed model demonstrated that upper-limb swing dynamics can be accurately represented by joint force moment profiles linearly combined with joint kinematics. Participants showed consistency in the swing plane regardless of skill level. The validated

Table 2.1. Continued

Study author	Sample	Procedure	Results
			method can estimate unmeasured movements based on the dynamic characteristics of the swing.
Lee et al. (2023)	18 elite female Korean golfers	Drive distance, medicine ball throw, isokinetic strength and power of trunk flexors and extensors, and isometric strength were assessed using a 3D electromagnetic motion analysis system.	Isometric trunk rotational strength and trunk extensor strength showed the highest correlation with drive distance. Isokinetic trunk extensor strength and medicine ball throw also showed high correlation with drive distance.
Li et al. (2023)	8 right-handed male recreational golfers	Assessment of erector spinae muscle activities, thoracolumbar region, and trunk kinematics during golf swings on three terrain slopes: 1) level, BLF; 2) ball above feet, BAF; 3) ball below feet, BBF. Surface electromyograms were recorded from the erector spinae muscles in the thoracic, T8, and lumbar, L3, regions. Swing parameters such as ball speed, launch angle, and X-factor separation were measured.	Muscle activity in BAF and BBF swings was significantly lower than in BLF during acceleration and early finish phases. The lumbar erector spinae was more active than the thoracic erector spinae during acceleration. There were no significant differences in X-factor angle or ball impact parameters between slopes, but ball speed, launch distance, and maximum height were higher in BLF.
Li et al. (2023)	6 male amateur golfers: 51.33 ± 9.75 years	Analysis of swing kinematics under three slope conditions: horizontal plane, ball below feet, and feet below ball, using the OptiTrack motion capture system and Caddie SC300 device to record shot parameters.	No significant differences were observed in total swing time or partial intervals, nor in body center of gravity, COG, variation between different slopes. However, slopes slightly influenced lateral COG displacement, restricting range of motion. Performance parameters, swing speed, ball speed, distance, and impact factor, also showed no significant differences. These results suggest that ground slope changes have limited impact on overall

Table 2.1. Continued

Study author	Sample	Procedure	Results
			kinematics, but may affect stability and postural control during the swing.
Lim et al. (2012)	5 male collegiate golfers	Four super VHS cameras and 2 force platforms were used to capture 3D kinematics and kinetics of the golf swing. EMG activity of the main muscles was recorded, and an EMG-assisted model was applied to estimate spinal loads.	Mean compressive load at L4-L5 was more than 6 times body weight during the downswing. Anterior and medial shear loads reached approximately 1.6 and 0.6 times body weight, respectively. High muscle activity was observed during the acceleration and follow-through phases, indicating a link between muscular co-contractions and spinal loads.
Liu et al. (2025)	Ten right-handed low-handicap male university players, handicap 1.29 ± 1.93 , mean age 20 years and 6 years of experience.	Participants performed ten full swings with driver, 5-iron, and 7-iron on a Kistler force platform synchronized with 16 Qualisys cameras. Angular velocities of the pelvis, trunk, lead upper limb, and club were analyzed, as well as ground reaction forces in vertical, anteroposterior, and lateral directions. The movement was segmented into backswing, transition, and downswing.	The driver showed longer and slower movements, with greater horizontal angular impulse, reflecting gradual energy accumulation. The 5-iron generated greater frontal angular impulse, associated with trajectory and impact-angle control. The 7-iron showed shorter and more precise transitions, with early acceleration of distal segments and greater anteroposterior force of the lead foot at impact. The kinematic pattern maintained the proximal-distal sequence, pelvis → trunk → upper limb → club. It was concluded that the driver prioritizes power and prolonged acceleration; the 5-iron combines power and control; and the 7-iron emphasizes accuracy and technical efficiency.

Table 2.1. Continued

Study author	Sample	Procedure	Results
McGuire et al. (2024)	Fifteen right-handed male university players, mean age 20.5 years; handicap 2.3 ± 1.0 , with competitive experience and no injuries.	Experimental 3D biomechanical study analyzing the effect of target distance, 30, 50, 70 yards, and full swing, on kinematic and temporal parameters of the short game. Eleven Vicon cameras, 250 Hz, with 65 reflective markers and a GCQuad simulator were used. Each player performed five successful shots per distance. Angular velocities, phase times, and proximal-distal sequence were measured.	Increased target distance significantly influenced phase duration and angular velocities. The backswing increased and the downswing shortened with distance; the transition phase was longest in the 70-yard condition. Angular velocities progressively increased in all segments, pelvis: $170 \rightarrow 387^\circ/\text{s}$; shoulders: $409 \rightarrow 706^\circ/\text{s}$; club: $965 \rightarrow 2089^\circ/\text{s}$. Proximal-distal sequences showed partial and inconsistent patterns, indicating that the short game requires specific coordination and distance-specific training.
Madrid et al. (2020)	66 golfers, handicap ≤ 3	Golfers performed maximum-effort shots with 3 club types, driver, 5-iron, and pitching wedge. Swing capture was performed using an optoelectronic motion capture system.	Higher clubhead speed was associated with shorter downswing phases, larger rotation ranges, greater hip/shoulder separation at impact, delayed transitions, faster rotations, and greater losses of angular velocity. There was no significant association with wrist cock angles/ranges or X-factor/stretching.
Mahadas et al. (2018)	Human model generated with OpenSim, integrating the Rajagopal body model and a golf club model.	OpenSim software was used to manipulate biomechanical parameters of the human model, generating a movement sequence during the golf swing. Positions were analyzed using MATLAB to calculate club speeds. Three scenarios were simulated to represent beginner, intermediate, and advanced players by adjusting time increments between positions.	Advanced players showed higher club speeds, up to 127 mph, compared with beginners, 30 mph. Reductions in delta-t, especially during the downswing transition, were associated with higher club impact speeds. The method is useful for analyzing complex biomechanical movements in sport and biomedicine.

Table 2.1. Continued

Study author	Sample	Procedure	Results
Marsan et al. (2019)	13 male golfers of various golf levels: handicap 20 to professional	Driver swings were performed in a motion capture laboratory. Seven methods based on different components of the angular velocity vector were tested.	The choice of angular velocity vector component critically influences the identified kinematic sequence. No method stood out as a reference for identifying the kinematic sequence of the golf swing.
Marta et al. (2016)	14 middle-aged non-elite golfers	Bilateral electromyography, EMG, of lower-limb muscles during the golf swing with three different clubs, pitching wedge, 7-iron, and 4-iron.	The highest levels of muscle activation occurred in the forward swing phase, with the semitendinosus and biceps femoris of the trail lower limb showing the greatest activation. The highest muscle activation was observed with the 4-iron.
Marta et al. (2016)	10 male golfers: 5 low-handicap and 5 high-handicap	Electromyographic, EMG, analysis of lower-limb muscles during the golf swing using a 7-iron. EMG was recorded in muscles such as biceps femoris, gluteus maximus, vastus medialis, tibialis anterior, among others. Swing phase was determined by high-speed 3D video analysis.	Low-handicap golfers performed the swing with shorter duration in the initial phases but longer duration in the late follow-through. They also showed earlier muscle activation peaks and greater activity in some lower-limb muscles, especially in the trail lower limb.
McHugh et al. (2022)	25 golfers, 13 proficient and 12 intermediate-level	Flexibility tests in 3 planes of motion, transverse, sagittal, and frontal. Analysis of trunk, pelvis, and hip movement during the swing and measurement of ball speed and shot distance.	Professional golfers showed greater flexibility in the transverse plane, shoulder, trunk, and hip, compared with intermediate-level golfers, with no significant differences in the sagittal and frontal planes. Hip flexibility in the transverse plane explained 48% of the variability in ball speed and 45% of total distance. Professional golfers had greater pelvis-shoulder separation, X-factor. Flexibility in the transverse plane is fundamental for golf proficiency.

Table 2.1. Continued

Study author	Sample	Procedure	Results
McHugh et al. (2024)	Thirty-three male players, mean age 37 years; handicap 8.1 ± 7.8 , divided into three groups: proficient, intermediate, and inexperienced.	Cross-sectional biomechanical study with driver, using a motion capture system, 10 cameras, 500 Hz, and two force platforms, 1000 Hz. Each player performed five shots, with the three best analyzed. Kinematic variables, X-factor, velocities and accelerations, kinetic variables, ground reaction forces, and temporal variables, proximal-distal sequence and peak times, were assessed.	Proficient players showed greater X-factor, 56° at the top; 36° at impact, greater pelvic velocity, $526^\circ/\text{s}$, and trunk deceleration, $-3214^\circ/\text{s}^2$. Greater unweighting of the lead foot, 76% reduction, and better temporal synchronization between segments were also observed. X-factor at impact explained 54% of handicap variance, and models including X-factor, velocities, and GRF explained up to 85% of ball speed. Axial rotation and eccentric trunk control were concluded to be determinants of performance and distance achieved.
McNally et al. (2019)	20 golfers, mean handicap 3.6 ± 3.4	Dynamic simulation of golf club behavior using motion capture of full swings, with 200 recorded shots. Static deflection and torsional and bending frequencies were tested.	The model simulated unique club bending patterns for each golfer. Mean error in club speed at impact ranged from -2.9% to 0.6% compared with empirical data. Torsional patterns were minimally relevant.
McNitt-Gray et al. (2013)	12 experienced golfers	Participants executed shots with a 6-iron, intentionally adjusting shot distance, short versus long, while using the same club. Ground reaction forces were measured with two force platforms, and three-dimensional kinematics were recorded simultaneously.	Horizontal resultant forces of the target-side foot were significantly lower when shot distance was reduced. There were no significant differences in the orientation of the horizontal resultant forces. Regulating force magnitude with minimal modification in force direction provides advantages in terms of muscle activation, coordination, and performance.
Milburn (1982)	Theoretical study with experimental support	Assessment of the principle of summation of segmental velocities in the golf swing. Kinematic analysis was used	The study confirmed that an efficient swing follows a segmental sequence: movements begin in the parts

Table 2.1. Continued

Study author	Sample	Procedure	Results
		to model how the sequence of segmental movements contributes to maximizing clubhead speed at impact.	closest to the center of mass, the hip, progressing toward distal segments, upper limbs and club. This results in greater velocity and force moment applied to the club at impact.
Mitchell et al. (2003)	65 male golfers divided into 3 age groups: university-aged, middle-aged, and senior	Biomechanical analysis of shoulder movements using a six-camera motion analysis system for bilateral three-dimensional recording during the driver swing. Mean joint range and terminal joint angles were compared between groups.	Senior golfers showed significantly lower maximum shoulder movement values than university-aged and middle-aged groups. In the backswing, seniors showed 38 degrees less external rotation of the trail upper-limb shoulder compared with university players. From address, seniors horizontally abducted the lead upper limb 18 degrees more than university players. Older golfers showed an overall reduction in range of motion for both shoulders in the vertical plane and for the lead upper-limb shoulder in the horizontal plane.
Morrison et al. (2016)	22 men divided into two ability groups: 11 with handicap 10-18, intermediate level, mean handicap 13.3 ± 2.8 , and 11 with handicap < 4 , high level, mean handicap -0.2 ± 2.0 .	Analysis of motor redundancy during the golf swing using Uncontrolled Manifold Analysis, UCM. Variances parallel, VUCM, and orthogonal, VOrth, to the UCM were calculated in relation to clubhead orientation and position.	More experienced players showed higher relative VUCM values than less experienced players across all variables analyzed. Motor synergy was observed in controlling clubhead orientation and combined variables, but not its position. Clubhead position variation was concentrated at impact, while orientation variation increased as the downswing progressed. Both groups showed greater control over clubhead position before impact and greater control over its orientation at

Table 2.1. Continued

Study author	Sample	Procedure	Results
			the start of the downswing. Achieving higher skill levels in golf may be more related to developing control over the body's redundant degrees of freedom than simply executing an ideal technique.
Morrison et al. (2018)	52 male golfers, 27 high-level and 25 intermediate-level	Analysis of clubhead trajectory near ball impact using an ellipse fit to describe the relationship between swing plane orientation and club impact characteristics. Each player performed 40 drives in a biomechanics laboratory. Ellipse eccentricity was investigated to determine associations with skill level.	Clubhead trajectory fitted an ellipse with a root mean square error of 1.2 mm. High-level golfers showed greater ellipse eccentricity. Club path and attack angle, generated from the ellipse-fitted clubhead trajectory, had errors of 2% and 3%, respectively.
Morrison et al. (2018)	52 male golfers, 27 highly skilled and 25 intermediate	Analysis of the delivery plane in the golf swing using principal component analysis and multiple regression to investigate the relationship between club movement and impact characteristics.	Lower club deviation from the delivery plane was associated with lower variability in impact location on the club, favoring greater shot consistency.
Mun et al. (2015)	15 professional golfers registered with the Korea Professional Golf Association	Six infrared cameras, 120 Hz, were used to analyze the kinematic relationship between lumbar spine rotational movement and hip joint movement during the golf swing. Markers were placed on the upper trunk, pelvis, and thighs to capture angular data, and the correlation between movements was assessed using cross-correlation analysis and angle-angle plots.	Rotational movement of the lead hip contributed more at the start of the downswing, while the lumbar spine contributed more near impact. A high mean correlation, $r = 0.81$, was observed between lumbar spine and hip movements, with similar coordination strategies among golfers. The study provides information on normal patterns for comparison with golfers with low back pain.
Murakami et al. (2016)	5 male players	Analysis of periodic X-ray images at 10 Hz during squats and golf swings. Analysis of knee kinematic parameters:	During the squat, the femur moved approximately 25 mm backward and rotated 19° externally relative to the

Table 2.1. Continued

Study author	Sample	Procedure	Results
		tibiofemoral flexion angle, anteroposterior, AP, translation, and internal-external rotation.	tibia. Screw-home movement near extension, bicondylar rollback between 20° and 120° of flexion, and medial pivot movement in additional flexion were observed. During the golf swing, the lead knee and trail knee showed approximately 5 mm and 4 mm of anteroposterior translation with 18° and 26° of axial rotation, respectively. Central pivot movement occurred from setup to the top of the backswing, lateral pivot movement from the top to ball impact, and medial pivot movement from impact to the end of follow-through.
Nabil et al. (2020)	30 male players, 10 healthy, 10 with tennis elbow, and 10 with golfer's elbow.	The normalized eccentric peak torque, NEPT, of the shoulder abductor and external rotator muscles was compared at different angular velocities, 60°/s and 120°/s. A Biodex isokinetic dynamometer was used to measure muscle strength.	NEPT of the shoulder abductor and external rotator muscles was significantly higher in the healthy control group compared with the tennis elbow and golfer's elbow groups at both angular velocities. Lack of stability in the upper kinetic chain may increase stress on distal joints, such as the elbow, and lead to recurrent injuries. Rehabilitation should include shoulder strengthening.
Nasirzadeh et al. (2025)	Twelve skilled players, 7 men and 5 women, right-handed, mean handicap 0.4 ± 1.6 and mean age 20.8 years.	Experimental study comparing normal swing and swing with a passive exosuit, composed of a diagonal elastic band between the shoulder and iliac crest. The device resisted rotation during the backswing and assisted during the downswing. Each participant performed ten shots per condition with their driver, recorded by 12 OptiTrack	Clubhead speed increased significantly, +2.55%, $p = 0.009$, with improvement in all participants. Maximum trunk recoil rate also increased, 273.3°/s versus 255.5°/s. Mechanical work in the transverse plane increased during the backswing, +20%, and downswing, +18%, without altering swing technique. The exosuit acted as

Table 2.1. Continued

Study author	Sample	Procedure	Results
		cameras and Kistler force platforms. Kinematic and mechanical variables were analyzed, including clubhead speed, X-factor, stretch and recoil rates, and segmental mechanical work.	an external tendon, amplifying the stretch-shortening cycle and increasing rotational power, with potential application in golf performance and proprioception training.
Nesbit and McGinnis (2009)	4 right-handed amateur golfers, 3 male and 1 female, with different swing types	Geometric and kinematic analysis of the golf swing hub path, including transfer of dynamic quantities from the golfer to the club.	The hub path has complex geometry with variable radii and a continuously moving center of curvature. A three-phase pattern based on radius was identified, corresponding to the downswing phases. A non-circular hub path was superior to one with a constant radius in minimizing kinetic load and generating higher clubhead speed. The shape of the hub path results from the search for balance between the golfer and the club, optimizing energy transfer.
Nesbit and McGinnis (2014)	4 golfers with different abilities and swing styles	Optimization of hand path and angular club trajectories to maximize clubhead speed at impact. A two-dimensional dynamic model was used to analyze a typical swing, taking into account each player's kinetic limitations, force, force moment, work, and power.	All subjects were able to increase clubhead speed at impact within their respective kinetic limitations by modifying hand path and angular club trajectories. The degree of speed improvement and kinetic reduction varied between subjects. Trajectory analysis allowed the kinetic weaknesses of each player to be identified, offering practical implications for improving swing efficiency without increasing kinetic demands.
O'Brien et al. (2020)	4 male golfers with different swing styles and abilities.	Participants performed driver swings in the laboratory and in the field, driving range. Kinematic and kinetic data were	Hub and clubhead trajectories were optimized to increase impact speed. It was observed that participants

Table 2.1. Continued

Study author	Sample	Procedure	Results
		collected using motion capture systems, Qualisys and CodaMotion CX-Sport, for motion analysis and modeling.	can improve their impact speeds while respecting their individual kinematic limitations. The revised model showed greater accuracy and applicability in laboratory and real-world environments.
Okazaki et al. (2025)	Sixteen right-handed male university students, aged 18-23 years, without a history of injuries or neuromuscular disease.	Experimental study using a rapid manual impact task analogous to the golf swing. Movement amplitude was varied across five levels, 11.5 to 27.5 cm, and participants performed 50 trials in total. Movement was captured in 2D, 240 Hz, with markers on the shoulder, elbow, wrist, club, and clubhead. Linear and angular velocities, peak times, directional accuracy, and movement variability were analyzed.	Increasing movement amplitude resulted in higher contact and peak velocity in the shaft and in the shoulder and elbow joints, $p < 0.001$, without compromising accuracy or increasing variability. Interarticular coordination remained stable, with a distal-proximal sequence, wrist → elbow → shoulder. The elbow was the main velocity generator, with angular values 6-7 times higher than those of the shoulder and wrist. It was concluded that greater amplitude improves impact velocity without loss of control, reflecting efficient and robust motor coordination.
Okuda et al. (2010)	13 experienced golfers, mean handicap = 0.8 ± 2.6 , and 17 less experienced golfers, mean handicap = 30.8 ± 5.5	Kinematic and kinetic data were obtained using high-speed 3D videography and force platforms while participants performed a full driver shot. Six temporal swing events were selected for analysis.	Experienced golfers showed earlier horizontal trunk rotation with rapid weight transfer to the trail foot during the backswing; earlier horizontal pelvic rotation with early weight transfer to the lead foot during the downswing; and lower upper-trunk horizontal rotation and greater posterior pelvic rotation in the follow-through.

Table 2.1. Continued

Study author	Sample	Procedure	Results
Park et al. (2018)	29 healthy right-handed golfers	Analysis of extension/flexion, valgus/varus, and external/internal rotation of the target-side knee during the downswing with driver and 5-iron. The downswing was divided into four sections.	A significant difference in valgus angle was found in the initial, second, and third sections for low-level golfers. High-level golfers and low-level golfers using the driver showed no significant differences. Variability in valgus angle may help improve performance in golfers using a 5-iron.
Peterson and McNitt-Gray (2018)	10 highly experienced golfers	Kinetic analysis of net joint moments, NJMs, of the target and trail lower limbs during swings with a 6-iron and driver.	NJMs increased in the ankle, knee, and hip of the target lower limb when using the driver. Different multi-joint control strategies were observed for the target and trail lower limbs. Most of the 3D support force moment was generated by NJMs perpendicular to the planes of the lower limbs.
Peterson et al. (2016)	11 highly experienced golfers	Analysis of components contributing to linear and angular impulse during the swing, using a 6-iron and a driver. Ground reaction forces in the horizontal component, horizontal GRF, ground reaction force angle, and the force moment generated by the support and lead lower limbs were quantified to determine how players regulate impulse while maintaining balance.	Angular impulse generated by the lower limbs was higher when using the driver compared with the 6-iron. Regulation of angular impulse varied between clubs and required intersegmental coordination of the lower limbs. Increased angular impulse with the driver was associated with increased horizontal force of the target lower limb, GRFh. The GRFh angle of the support lower limb remained similar between clubs, while the target lower limb aligned more with the target line. Linear impulse along the target line decreased, contributing to maintenance of postural balance.

Table 2.1. Continued

Study author	Sample	Procedure	Results
Peterson et al. (2019)	9 highly experienced golfers	Analysis of linear and angular impulse during the swing under different address positions, normal stance, trail leg elevated, and lead leg elevated, using a 6-iron. Components of impulse generated by the trail and lead legs were quantified and compared.	Net angular impulse showed no significant differences between conditions. Angular impulse of the lead leg was higher in the lead-leg-elevated condition compared with the trail-leg-elevated condition. Regulation of linear and angular impulse occurred through increased base width and redirection of the horizontal component of ground reaction force, making it more parallel to the target line. Linear impulse perpendicular to the target remained close to zero, or slightly posterior, while impulse parallel to the target was lower in the lead-leg-elevated condition.
Pink et al. (1990)	6 male professional golfers, mean age 35 years, and 7 female professional golfers, mean age 32 years, all right-handed and with healthy shoulders.	Electromyography, EMG, of 8 shoulder muscles, infraspinatus, supraspinatus, subscapularis, latissimus dorsi, pectoralis major, and anterior, middle, and posterior deltoids, in both shoulders during the golf swing. High-speed cameras were used to synchronize movement across five phases: takeaway, forward swing, acceleration, early follow-through, and late follow-through.	The infraspinatus and supraspinatus muscles acted mainly at the extremes of shoulder range of motion. The subscapularis and pectoralis major were most active during acceleration; the latissimus dorsi during the forward swing; and the anterior deltoid during the forward swing and follow-through. The middle and posterior deltoids did not show relevant activation patterns.
Pink et al. (1993)	23 golfers with handicap of 5 or lower	Surface electromyography of the abdominal oblique and erector spinae muscles bilaterally during the golf swing. Electrodes were combined with high-speed video recording to analyze trunk muscle activation patterns.	Muscle activity was reduced during the takeaway phase, below 30% of the maximum test, but high and constant throughout the rest of the swing, above 30% of the

Table 2.1. Continued

Study author	Sample	Procedure	Results
			maximum test, except in the contralateral erector spinae at the end of follow-through, 28%.
Purevsuren et al. (2020)	10 male professional golfers, mean age 23.2 ± 1.6 years	3D motion capture during the golf swing with inverse dynamics analysis and computational modeling to calculate forces and strains in the anterior cruciate ligament, ACL, of the lead knee.	The high-ACL-load group showed greater knee adduction moments and upper-body movement immediately after ball impact, contributing to greater ACL force. Mean maximum ACL force was 841.8 ± 437.1 N.
Rusdiana et al. (2021)	6 experienced golfers and 6 amateurs, mean age: 25.4 ± 36.2 years	Kinematic differences in the long swing between experienced and amateur players were analyzed using a 3D approach. Participants performed 10 shots each.	Experienced players showed greater ball speed and significantly higher angular rotation of the hips and shoulders.
Sanders and Owens (1992)	6 junior golfers and 6 elite golfers, all male	Each player performed 10 swings with a 3-wood. Movements of reflective markers placed on the highest point of the head and on the participant's chin, as well as at three points along the club shaft, were captured.	In elite players, the swing hub was not fixed, but the hub movement pattern was consistent. The radius from the hub to the club reached a maximum near impact. In junior players, maximum radius occurred after impact and hub patterns were inconsistent.
Sell et al. (2007)	257 male golfers, divided into three groups according to handicap: HCP < 0, HCP 1-9, and HCP 10-20; mean age: 45.5 ± 12.8 years	Assessment of strength, trunk, shoulder, hip, flexibility, trunk, shoulder, hip, and single-leg balance, eyes open. Results were compared across the 3 skill levels.	Golfers in the highest-skill group, HCP < 0, showed significantly greater strength in the hip, trunk, and shoulders, as well as greater flexibility in the hip, trunk, and shoulders and better balance compared with golfers in the lowest-skill group, HCP 10-20. Specific physical characteristics, such as strength, flexibility, and balance, are associated with greater golf proficiency.

Table 2.1. Continued

Study author	Sample	Procedure	Results
Silva et al. (2013)	8 amateur male right-handed golfers, 52.0 $\pm$ 7.4 years; handicap 15.7 $\pm$ 3.2.	Participants performed 5 precision swings with a pitching wedge, <100 m, and 5 long-distance swings with a 4-iron, >150 m. Muscle activation was analyzed using EMG during the golf swing. Two methods of detecting muscle activation threshold and the influence of different muscles and clubs on muscle activation timing were compared.	The external oblique was the first muscle activated, approximately 1295 ms before impact. The rectus abdominis showed the highest agreement between methods, while the spinal erector showed low agreement, possibly due to its continuous postural activity. No significant differences were observed between clubs.
Smith et al. (2016)	15 right-handed golfers, mean age 30 $\pm$ 10 years, handicap 1-29	Two-dimensional, 2D, and three-dimensional, 3D, methods were compared for analyzing trunk kinematic variables, flexion/extension, lateral bending, and axial rotation, and X-factor during the golf swing. The Vicon Nexus system with 13 cameras, 250 Hz, was used.	Significant differences were found between 2D and 3D methods for trunk flexion at the top of the backswing, -6.5°, and lateral bending at impact, 8.7°. The 3D method is more accurate for capturing trunk kinematics and X-factor, avoiding projection errors present in 2D.
Sorbie et al. (2018)	15 right-handed golfers	Players performed a total of 20 swings in random order using driver, 4-iron, 7-iron, and pitching wedge. Surface EMG was recorded from the lead and trail sides of the thoracic and lumbar regions of the erector spinae muscle, T8, L1, and L5 lateral to the spinous process. High-speed video analysis was used to identify the backswing, forward swing, acceleration, early follow-through, and late follow-through phases.	No significant differences were found in muscle activation levels between clubs, driver, 4-iron, 7-iron, and pitching wedge. The highest mean activation levels of thoracic and lumbar ES muscles were displayed in the forward swing, 67-99% MVC, and acceleration, 83-106% MVC, phases for all clubs tested. There were no significant differences in muscle activity between tested clubs in the thoracic and lumbar regions of the ES muscle.
Steele et al. (2018)	11 professional golfers and 5 amateurs	Upper torso and pelvic rotational velocity during the golf swing was analyzed using 3D motion analysis.	Professional players demonstrated consistency in rotational velocities, with low variability, especially in

Table 2.1. Continued

Study author	Sample	Procedure	Results
		Professional and amateur golfers were compared, focusing on angular velocity during different swing phases, including impact and follow-through.	upper torso and pelvic rotation during the downswing. Amateurs showed reduced rotational velocities at impact and follow-through compared with professionals. Significant differences were observed in peak rotational velocity of the pelvis and torso between professionals and amateurs, highlighting the importance of follow-through in performance.
Suhara et al. (2023)	28 elite golfers, 14 men: mean age 19.6 ± 1.9 years, handicap 4.4 ± 0.9 ; 14 women: mean age 17.7 ± 1.4 years, handicap 6.2 ± 0.7	Assessment of the relationship between clubhead speed, CHS, and explosive strength/muscle strength of the hip and trunk muscles. Hip extension-flexion and trunk rotation force moment at 60 and 180°/s, countermovement jump power, CMJ, and medicine ball throw distance, BOMB, were measured. CHS was measured with Doppler radar, TrackMan.	CHS showed a positive correlation with maximum right hip extension force moment at 180°/s, maximum CMJ power, and medicine ball throw distance. Hip and trunk extensor strength is important for CHS. Concentric trunk rotational strength was not correlated with CHS, suggesting that it may not be directly involved in swing performance.
Suwondit et al. (2022)	22 golfers, aged 17-33 years	Core muscle strength and power were assessed through medicine ball throw and weight machine exercises. Hip and pelvic biomechanical characteristics were measured with a 3D motion analysis system. Performance was assessed with a golf simulator, measuring clubhead speed, ball speed, and ball distance.	Significant correlations were found between left hip abduction, in right-handed players, at the top of the swing and golf performance, $r = -0.43$ to -0.51 ; $p < 0.05$. Moderate correlations were also found between core muscle strength/power and hip and pelvic biomechanical variables, $r = 0.43$ - 0.54 ; $p < 0.05$. These results suggest that greater core and pelvic stability may contribute to a more effective swing.

Table 2.1. Continued

Study author	Sample	Procedure	Results
Takagi et al. (2017)	8 right-handed golfers, 4 men and 4 women; mean age: 18 years; mean handicap: 2.6	A 3D motion capture system, 17 cameras, 500 Hz, was used to analyze the relationships between club shaft movements, horizontal angle, plane inclination, and rotation angle, and clubface orientation at impact. A total of 45 shots were performed, with parameter sensitivity analyzed through simulated perturbations.	The horizontal angle of the swing plane affected the horizontal orientation of the clubface by 100%. Plane inclination influenced the vertical and horizontal face angles by 74% and 68%, respectively. Shaft rotation had a significant impact on face angles, contributing -67% vertically and 75% horizontally. The method showed high accuracy for investigating control of clubface orientation.
Takagi et al. (2017)	8 right-handed golfers, 4 men and 4 women; mean age: 18 years; mean handicap: 2.6	A 3D motion capture system, 17 cameras, 500 Hz, was used to analyze the relationships between club shaft movements, horizontal angle, plane inclination, and rotation angle, and clubface orientation at impact. A total of 45 shots were performed, with parameter sensitivity analyzed through simulated perturbations.	The horizontal angle of the swing plane affected the horizontal orientation of the clubface by 100%. Plane inclination influenced the vertical and horizontal face angles by 74% and 68%, respectively. Shaft rotation had a significant impact on face angles, contributing -67% vertically and 75% horizontally. The method showed high accuracy for investigating control of clubface orientation.
Teu et al. (2006)	1 semi-professional golfer, low handicap	Electrogoniometers, 1000 Hz, attached to the left upper limb were used to capture joint rotations during the swing. Club speed was analyzed using the double Euler angle algorithm and compared with video analysis.	The torso was the main contributor to club speed, 16 m/s, followed by wrist extension, 7.6 m/s, and upper-limb abduction, 6 m/s.
Tinmark et al. (2010)	45 golfers, 11 male tournament professionals, 21 male amateurs, and 13 female elite players	Players performed partial wedge shots for submaximal distances, 40, 55, and 70 m, and full shots with a 5-iron and driver for maximum distance. Movements of the	A significant proximal-distal temporal relationship and sequential increase in maximum angular velocity, peak, were observed under all shot conditions, for both sexes

Table 2.1. Continued

Study author	Sample	Procedure	Results
		pelvis, upper trunk, and hands were recorded in 3D with a Polhemus Liberty electromagnetic tracking system at 240 Hz, and the magnitude of the resultant angular velocity vector of each segment was calculated.	and skill levels. Results indicated coordinated use of intersegmental force moments, generated by dynamic interaction between adjacent body segments, suggesting efficient transfer of energy and angular velocity along the kinetic chain.
Turner et al. (2020)	6 participants for free movements; 16 golfers, 24.6 ± 3.2 years, mean handicap 16.5 ± 8.6, for dynamic shots	3D capture of movements using a Vicon optoelectronic system, with analysis of wrist angles in different types of free movement and during the golf swing.	Marker location significantly influenced the joint angles obtained, especially wrist axial rotation. Standardization of marker placement is recommended to ensure greater consistency and reliability of results.
van der Walt et al. (2024)	Six participants, four men and two women, aged 27-38 years, heights between 1.59 m and 1.89 m, BMI between 25 and 36, including beginner and experienced players.	Pilot study aimed at identifying the optimal positions for placing inertial measurement units, IMUs, during the golf swing. Eight positions on the dominant side of the body were tested, from ankle to shoulder. Sensors recorded acceleration, angular velocity, and orientation, and were compared for stability and noise.	The most reliable positions were the lumbar region and the lead-side wrist, which showed consistent data and high correlation with actual club movement. The study demonstrated that a well-positioned IMU system can accurately replace optical 3D capture systems, offering portable, low-cost measurements applicable in field contexts.
Vasudevan et al. (2016)	18 healthy men, 9 golfers and 9 tennis players, mean age: 22.2 years.	Surface electromyography, EMG, was used to determine the muscle activation sequence during the golf and tennis swings. Three training exercises were also assessed: cable wood chop, rotational medicine ball throw against the wall, and Turning Point 4.0 Rotational Platform. Participants performed 5 repetitions of each exercise and sport movement.	The assessed exercises partially replicated the natural muscle activation sequences observed in golf and tennis swings. Turning Point 4.0 showed higher correlation with the tennis swing than with the golf swing. The relevance of specific exercises for improving performance and preventing injuries was highlighted,

Table 2.1. Continued

Study author	Sample	Procedure	Results
			but future studies with larger samples are needed to confirm the results.
Verikas et al. (2016)	15 golfers, about 5 shots per player	Analysis of muscle activity during the golf swing with a 7-iron, using 8-channel electromyography, EMG, to record muscle activity of the upper limbs and shoulders, flexor carpi radialis, extensor digitorum communis, rhomboid, and trapezius. Muscle activation profiles were analyzed, and machine learning models, random forest, were used to predict shot effectiveness based on EMG data.	Persistent muscle activation patterns were identified in players, with 2 main activity peaks in each EMG channel during the swing. The predictive model showed an error rate of 24.3% for clubhead speed prediction and 31.7% for carry distance. The analysis highlighted the importance of muscle activity on both sides of the body, and the use of EMG-derived feature sets was useful in predicting shot effectiveness.
Verikas et al. (2017)	16 elite golfers, 11 men and 5 women	Participants performed five normal golf shots using a 7-iron. EMG signals were recorded from 8 muscles, and kinematic data were captured using a motion capture system.	Strong linear relationships were observed between EMG data and peak rotational velocities of the thorax and pelvis. Prediction accuracy for the thorax: $R^2 = 0.958$; pelvis: $R^2 = 0.943$.
Wang et al. (2015)	7 golfers from a university team, handicap: 0-12	Swing speed and impact accuracy tests using a 5-iron. A force platform and an EMG system were used to assess reaction force and muscle activity during the swing, and high-speed cameras were used to measure club speed and displacement of the center of rotation, C7, in the impact accuracy test.	Significant differences in clubhead speed were found between different movement sequences and muscle contraction patterns. Displacement of the center of rotation, C7, differed significantly between impact marks on the clubface. Vertical reaction force in the lead lower-limb foot before impact and contraction of the lead-side latissimus dorsi before the trail-side pectoralis major indicate greater ability to promote more efficient and faster ball impact.

Table 2.1. Continued

Study author	Sample	Procedure	Results
Ward et al. (2015)	15 elite golfers and 13 recreational golfers	Assessment of sagittal hip kinematics during the golf swing using retroreflective markers and a Qualisys motion capture system. Ball trajectory was measured using FlightScope 3D Doppler radar.	No significant differences were found in sagittal-plane hip kinematic measures between elite and recreational golfers. There was no significant correlation between hip kinematics and ball trajectory determinants. No performance advantages were found for posteriorly tilting the hip during the downswing.
Watkins et al. (1996)	13 male professional golfers	Muscle activity was assessed using surface electromyography electrodes. Activity of the right and left abdominal obliques, right and left gluteus maximus, right and left erector spinae, and upper and lower rectus abdominis was recorded during the golfer's swing. Signals were synchronized with video images of the swing phases, recorded with a high-speed camera. The swing was divided into five phases: takeaway, forward swing, acceleration, early follow-through, and late follow-through.	Reproducible patterns of trunk muscle activity were observed throughout all swing phases. Trunk muscles are important in stabilizing and controlling the load response for maximum power and accuracy in the golfer's swing.
Yang et al. (2024)	Twenty right-handed male amateur players, aged 20-30 years: ten low-handicap, 4.3 ± 2.4 , and ten high-handicap, 29.1 ± 5.4 .	Experimental study conducted in a biomechanics laboratory. Each player used three 7-iron clubs with different shaft weights, light: 77 g; medium: 98 g; heavy: 114 g, while maintaining the same head and grip. Kinematic variables were recorded with nine infrared cameras, 200 Hz, and a force platform, 1000 Hz, and performance was measured with a FlightScope Launch	Low-handicap players showed greater trunk rotation, X-factor, and wrist angle, as well as higher angular velocities, $p < 0.05$. The light shaft significantly increased clubhead speed, +2.2%, ball speed, and total distance, especially in more experienced players. The high-handicap group showed greater center-of-gravity displacement toward the trail side, reflecting poorer

Table 2.1. Continued

Study author	Sample	Procedure	Results
		Monitor. Each participant performed five shots per club, with the two best analyzed.	postural control. It was concluded that lighter shafts improve distance without altering swing mechanics, with more evident effects in more skilled golfers.
Zemková et al. (2019)	17 golfers, 17 ice hockey players, 21 tennis players, and 39 healthy control individuals	Measurement of maximum and mean power during trunk rotations to each side, using loads of 5.5 kg, 10.5 kg, 15.5 kg, and 20 kg applied to the dorsal region.	Maximum and mean power were significantly higher on the dominant side compared with the non-dominant side in ice hockey players, tennis players, and golfers across different loads. The D/ND index was highest in ice hockey players, followed by golfers and tennis players. No significant differences were found in the control group. Trunk power asymmetries may reflect the asymmetric loading of different sports.
Zheng et al. (2008)	25 LPGA professional golfers and 25 PGA professional golfers	Kinematic analysis with an optoelectronic system at 240 Hz. Comparison of body segment angles and angular velocities during the swing.	At peak backswing, significant differences were observed in trunk inclination and pelvic orientation between groups. Pelvic rotation at ball impact was significantly different. LPGA players showed lower angular velocities in the club shaft, lead upper-limb wrist, trail upper-limb wrist, and elbow extension compared with PGA players. Biomechanical differences between sexes were identified, especially in the wrist and elbow joints.
Zheng et al. (2008)	72 male golfers: 18 professionals, 18 low-handicap,	Kinematic analysis of the golf swing using an optoelectronic system at 240 Hz. Displacement, angular velocity, and temporal parameters were calculated during	Professional and low-handicap golfers showed greater magnitudes of horizontal adduction of the lead upper-limb shoulder, external rotation of the trail upper-limb

Table 2.1. Continued

Study author	Sample	Procedure	Results
	18 mid-handicap, and 18 high-handicap	different swing phases, including the top of the backswing and ball contact.	shoulder, and trunk rotation at the top of the swing. During the downswing, professionals generated higher angular velocities in the club shaft, lead upper-limb elbow extension, and lead and trail upper-limb wrists. Mid- and high-handicap golfers displayed inadequate mechanics, which may contribute to golf-related injuries.
Zhou et al. (2022)	11 professional golfers and 5 amateurs	Biomechanical analysis of the golf swing using 3D kinematics to measure rotational velocities of the pelvis and upper torso. Nine kinematic metrics were tested to create a Swing Performance Index, SPI.	The SPI, using maximum pelvic rotational velocity pre-impact, pelvic velocity at impact, and maximum post-impact torso velocity, significantly differentiated professionals, mean SPI: 100 ± 10 , from amateurs, mean SPI: 82 ± 4 , with an AUC of 0.97. The index has potential to provide quantified feedback on swing technique.
Zou and MacFarlane (2024)	Twenty men aged 18-45 years, divided into three groups: ten players, five low-handicap 0-7 and five mid-handicap 8-19, and ten non-players, all right-handed and without injuries.	Cross-sectional study comparing muscle strength and swing performance. Isometric and isokinetic strength of the biceps and triceps muscles of the lead upper limb was measured with a Primus RS dynamometer. The swing was analyzed with the Optishot 2 simulator using five clubs, SW, 9I, 7I, 5I, and 3W. Shot distance, face angle, swing path, and impact point on the clubface were assessed.	Players showed greater isometric triceps strength and a lower biceps/triceps ratio than non-players, with a tendency toward greater eccentric triceps strength. Low-handicap players produced longer shots and more centered impacts. Triceps strength correlated positively with distance, while high biceps/triceps ratios were associated with lower performance. It was concluded that triceps strength dominance favors impact stability and consistency, with contact-point accuracy being a

Table 2.1. Continued

Study author	Sample	Procedure	Results
			more sensitive indicator of proficiency than distance or shot angle.

2.3.2. Motor Control, Stability, and Weight Distribution

The relationships between motor control, stability, and weight distribution play a fundamental role in golf biomechanics, directly influencing swing effectiveness and consistency. The studies analyzed in this section demonstrate that the way players manage stability and weight distribution during the swing affects performance, club speed, and shot accuracy (Table 2.2).

2.3.2.1. Balance strategies and weight transfer

Mears et al. (2018) applied principal component analysis, PCA, to identify biomechanical patterns associated with performance, observing that greater axial rotation of the pelvis and thorax during the backswing is correlated with better performance. This efficient rotation facilitates weight transfer and increases torque during the downswing. Similarly, Jones et al. (2023) identified two main center of pressure, COP, control patterns: front-foot, with weight concentrated on the lead foot, and reverse, with weight shifted backward during the downswing. Players with lower handicaps and higher club speed tend to adopt the front-foot style, reinforcing the importance of appropriate pressure displacement to optimize power generation.

Severin et al. (2022) showed that different clubs require distinct balance adjustments as well as different joint force moments. The driver generates greater clubhead speed, whereas the 6-iron requires greater support moment in the lead lower limb during the follow-through. This club-specific postural adaptation is essential for movement effectiveness and consistency.

Navarro et al. (2022) observed that plantar pressure distribution differs between professional and amateur players: the former use the ground more efficiently, maximizing stability and energy transfer. Gryc et al. (2015) reinforced that progressive weight displacement toward the target is determinant for achieving higher club speeds, with weight transfer being a direct predictor of swing power. McNally et al. (2014) added that the mechanical work of the lower limbs is one of the main determinants of clubhead speed, confirming the role of lower-limb force in power generation.

Ball and Best (2011; 2007) identified that the front-foot style is associated with a greater range of COP displacement and faster weight transfer, resulting in higher club speed. The

reverse style, in contrast, is characterized by a more forward COP position in the toe region at impact, highlighting differences in individual balance strategy.

2.3.2.2. Influence of terrain slopes

Blenkinsop et al. (2018) and Hiley et al. (2021) demonstrated that sloped surfaces modify COP trajectory, launch angle, and ball spin. Uphill shots tend to deviate to the left, whereas downhill shots deviate to the right.

Gerçek et al. (2025) tested the 6-iron under level, uphill, and ball-above-feet conditions. Although the overall weight-transfer pattern was maintained, the ball-above-feet condition increased anteroposterior sway and reduced distance and club speed, indicating that postural control directly affects shot effectiveness on sloped surfaces.

Players adjust their posture to compensate for these changes, but variability in adaptation strategies suggests that training should include situations with different slopes in order to develop individualized and robust postural responses.

2.3.2.3. Postural stability and motor control

Odabaş et al. (2019) identified significant differences in loading between the dominant and non-dominant feet in players from the Turkish National Team, reinforcing the importance of balance training to optimize load distribution and improve dynamic stability.

Jones et al. (2018; 2024) found that more experienced players show lower intraindividual variability in ground reaction forces, both with the driver and the 5-iron, indicating that consistency in force application to the ground is a marker of technical proficiency.

Stokes et al. (2023) showed that a more open foot stance reduces force moments in the lead knee, decreasing joint stress. This result is aligned with Lynn and Noffal (2010), who found that external foot rotation during the stance reduces knee adduction moments, suggesting an effective injury-prevention strategy.

Green et al. (2015) associated dynamic balance with greater drive distance, while Choi, Lee, et al. (2016) observed that professional players show less separation between the center of mass and COP, indicating better postural control and greater swing stability. Gulgin et al. (2014) further showed that mobility or balance limitations, such as inability to perform a deep squat or maintain single-leg support, are associated with technical faults such as early hip extension or loss of optimal posture.

Marshall and Llewellyn (2017) confirmed that players with better performance in balance tests, BESS Test, achieve greater mean drive distances. Interestingly, they observed a negative correlation between excessive flexibility and performance, suggesting that stability may be more determinant than range of motion for swing efficiency.

2.3.2.4. Weight transfer, force, and individual patterns

Pataky (2014) demonstrated that lateral plantar pressure on the target-side foot is positively correlated with clubhead speed, emphasizing that the location of weight transfer is as relevant as its magnitude.

Choi et al. (2016; 2015) observed that experienced players show better dynamic control and flexibility in the support knee, allowing forces to be absorbed more efficiently. Egret et al. (2004) added that experts exhibit greater range of motion and stability in the lower limbs, ensuring a solid base and a fluid transition of body weight.

Takagi et al. (2021) showed that flexion and adduction of the lead hip, together with extension and abduction of the trail hip, are the main factors influencing axial rotation, reinforcing the importance of coordination between body segments for power generation.

Foxworth et al. (2013) found that younger players produce greater hip force moments, but that older players compensate for this loss of force through technical adjustments.

Callaway et al. (2012) demonstrated that gluteus maximus and gluteus medius strength correlates with pelvic rotational velocity, especially in low-handicap players, highlighting the role of core stability and strength in swing efficiency. Booysen et al. (2017) observed altered hip motor control patterns in elite players, including pelvic and trunk compensations potentially associated with femoroacetabular impingement, emphasizing the importance of technical control in injury prevention.

Wells et al. (2020) found no significant correlation between vertical symmetry of reaction forces and club speed, suggesting that performance depends more on individually optimized weight-transfer patterns than on absolute symmetry. Sohn and Choi (2013) reinforced this idea by demonstrating that performance variability is more closely related to individual biomechanical characteristics than to absolute power level, supporting personalized training approaches.

2.3.2.5. Specific adaptations by club type

Lindsay et al. (2002) found that the use of the 7-iron emphasizes lateral trunk movement more than the driver, suggesting that each club requires specific postural adjustments. Training that simulates these variations may therefore increase consistency and technical transfer between clubs. In addition, Odabaş et al. (2019) demonstrated that different mechanical demands of the swing are associated with variations in load distribution between the lower limbs, particularly between the dominant and non-dominant limbs, in elite players, reinforcing that postural assessment and balance training should be considered central components in technical and preventive planning.

Thus, the various studies indicate that swing effectiveness depends on a refined interaction between postural control, segmental stability, and coordination of weight transfer. More proficient players show more consistent force and balance patterns, use the ground more predictably, and adjust the body efficiently to the demands of terrain and equipment. Stability is therefore not only a mechanical requirement, but also an integrative element of motor control that supports both performance and injury prevention in golf.

Table 2.2. Characteristics of the selected studies addressing motor control, balance, and weight distribution.

Study author	Sample	Procedure	Results
Ball & Best, 2007	39 golfers with a Front Foot style and 19 golfers with a Reverse style	Assessment of the center of pressure, COP, during the driver swing using force platforms. COP displacement, amplitude, and migration timing parameters were analyzed.	For the Front Foot group, greater COP displacement amplitude and faster COP movement during the downswing were associated with higher clubhead speed at impact. For the Reverse group, positioning the COP farther from the trail foot at the end of the backswing and faster COP transfer toward the trail foot at impact were associated with higher clubhead speed at impact.
Ball & Best, 2012	5 golfers, professionals and amateurs	Measurement of COP position and velocity using two force platforms across 50 swings, with regression analysis to relate these parameters to clubhead speed.	The study confirmed the importance of weight transfer for clubhead speed, with greater weight transfer amplitude associated with higher clubhead speed. Individual analysis revealed different and significant relationships that were not identified in group analyses. The rate of weight transfer at swing events was also significant. Individualized analysis should be part of biomechanical assessment of sports performance.
Blenkinsop et al. (2018)	12 elite male golfers	Golfers performed 30 shots with a 6-iron from 5° terrain slopes, with 3D kinematic and kinetic data collection and performance measurement using a launch monitor.	Weight transfer shifted toward the lower foot, leading players to adopt a wider stance and position the ball closer to the upper foot at address. Ball speed was not significantly affected by slope, but launch angle and lateral curvature of ball trajectory were altered. Players tended to hit more to the left on uphill slopes and more to

Table 2.2. Continued

Study author	Sample	Procedure	Results
			the right on downhill slopes. No consistent compensatory adjustments in shot line or azimuth were observed, with final shot dispersion associated with lateral curvature.
Booyesen et al. (2017)	58 elite professional golfers, mean age 29.5 years, age range 18-43 years	A movement screening tool was used to observe movement control patterns of the hip and lower limbs. Five tests were performed, including the small knee bend, SKB, and hip abduction with lateral rotation. Movement quality was assessed against reference criteria.	Altered movement patterns were observed in all tests, particularly poor control of hip medial rotation and flexion during the SKB. Pelvic tilt and trunk flexion compensations were observed. Poor hip control may be related to the development of femoroacetabular impingement, FAI, which may contribute to hip osteoarthritis, OA.
Callaway et al. (2012)	56 golfers with different handicap levels	Gluteus maximus and gluteus medius strength was measured using a handheld dynamometer. Pelvic rotational velocity was assessed using triaxial inertial sensors, accelerometers, gyroscopes, and magnetometers, integrated into a K-Vest, K-Motion, system. Each participant performed 5 swings, and rotational velocity was recorded.	The study found a significant relationship between pelvic rotational velocity and gluteal muscle strength in low-handicap golfers. Low-handicap golfers demonstrated greater pelvic rotational velocity and greater gluteus maximus and medius strength compared with high-handicap golfers.
Choi et al. (2015)	18 experienced golfers and 23 inexperienced golfers	Six infrared cameras and two force platforms were used to record swing movement. Anatomical angles and moments were calculated, and quasi-stiffness was determined from the instantaneous slope of moment-angle curves.	The support knee of experienced golfers showed shorter joint stabilization time compared with the lower-skill group. The support knee also showed greater flexibility than the swing knee in the higher-skill group, as well as compared with both knees of the lower-skill group.

Table 2.2. Continued

Study author	Sample	Procedure	Results
Choi et al. (2016)	50 participants divided into 3 groups: professional, advanced, and novice	Six infrared cameras and two force platforms were used to measure dynamic changes in the center of mass, COM, and COP.	Professional golfers generally showed smaller COM and COP displacement and velocity compared with amateur golfers. Professionals showed significantly greater COM displacement in the lead direction than advanced amateurs. COM-COP separation decreased as performance level increased, indicating that professionals have superior dynamic balance control, compensating for greater COM variation through better COP displacement control, resulting in a more stable swing mechanism.
Choi et al. (2016)	12 professional golfers, 13 amateurs, and 10 beginners	COM and COP trajectories were measured using six infrared cameras, two force platforms, and SB-Clinic software.	Professional golfers showed lower COM-COP inclination angle and angular velocity compared with beginners in the forward/backward direction. The professional group also showed lower normalized COM-COP angular impulse values in all directions. Professionals tend to display better dynamic balance, associated with appropriate postural control.
Egret et al. (2004)	14 male golfers, 7 specialists and 7 experienced players	A VICON™ motion capture system with five cameras operating at 50 Hz was used to analyze golf swing kinematics. Movement amplitude and weight transfer were assessed.	Specialists displayed greater flexibility and maximum range of motion compared with experienced golfers. Specialist golfers had a shorter backswing. Lower-limb stability and weight transfer were more effective in specialists. Skill level significantly influenced spatial and temporal swing patterns, with specialists demonstrating more efficient coordination.

Table 2.2. Continued

Study author	Sample	Procedure	Results
Foxworth et al. (2013)	20 male golfers divided into two groups: young group, mean $\pm$ SD age 25.1 ± 3.1 years, and senior group, mean age 56.9 ± 4.7 years	Each subject performed 10 golf swings with their personal driver. A motion capture system and force platforms were used to obtain kinematic and kinetic data. Inverse dynamics analyses calculated 3D hip force moments of the support and lead limbs.	External hip rotation moment in the support limb was significantly higher in the young group than in the senior group, and higher in the support limb than in the lead limb. When adjusted for clubhead speed, hip moments during the swing were comparable between young and senior groups, except for external hip rotation moment in the support limb. The largest hip moment found was the extensor moment in the support limb.
Gerçek et al. (2025)	Twenty elite players, fourteen men and six women, right-handed, mean age 23.7 ± 7 years, body mass 69.6 ± 18.1 kg, height 175.6 ± 9.7 cm, handicap between 0 and 5, all with more than eight years of continuous training.	Experimental study with shots performed under three terrain conditions: level, uphill, 10° , and ball above feet. Weight transfer was recorded using a TekScan MatScan® force platform, and performance was measured with the TrackMan® Golf Radar System. Each participant performed twelve shots, four per condition, after warm-up and familiarization trials.	No significant differences were observed in the overall weight-transfer pattern between conditions, but greater anteroposterior sway and center-of-force area were found in the ball-above-feet condition. Shots from this slope resulted in shorter distance and lower club speed, while uphill shots showed a higher angle of attack. Positive correlations were identified between anteroposterior sway and club speed, indicating that postural control directly influences swing effectiveness. The ball-above-feet position was concluded to compromise balance and weight transfer, reducing movement efficiency.
Green et al. (2015)	18 golfers, mean handicap 11 ± 6 ; mean experience 18 ± 15 years	Measurement of drive distance and accuracy. Balance was assessed using a modified stork test, and hand-eye coordination using a 3D maze.	Balance, especially mean balance duration on both lower limbs and on each lower limb individually, was significantly correlated with drive distance. Hand-eye coordination was negatively correlated with total drive

Table 2.2. Continued

Study author	Sample	Procedure	Results
			distance, but not with the contact point between the clubface and the ball.
Gryc et al. (2015)	4 right-handed elite golfers, age 29 ± 8 years	Players performed 20 shots with their own 7-iron, hitting golf balls from artificial pro-turf, commonly used in driving ranges, into a net placed 3.5 m away. Swing kinematics were analyzed using the CODA Motion system, and weight transfer was measured with KISTLER force platforms.	High intraindividual and interindividual stability was observed during the downswing phase. Greater interindividual variability was found during the backswing phase. The strong relationship between club speed and weight transfer indicated that players used weight transfer toward the target to generate extra energy in the ball. Weight-transfer strategies varied between players.
Gulgin et al. (2014)	36 golfers, mean age 25.4 years	Twelve physical tests of strength, flexibility, and balance were assessed using the TPI Level 1 tool, followed by video analysis of 14 common golf swing faults.	Significant associations were found between physical limitations and swing faults: toe touch and early hip extension, right side bridge with early hip extension, and loss of posture. Golfers unable to perform the deep squat with the upper limbs overhead or single-leg balance on the left side were 2-3 times more likely to show early hip extension, loss of posture, or sliding during the swing.
Hiley et al. (2021)	12 male mid-handicap golfers	Assessment of COP movement, alignment, and golf shot outcome on flat surfaces, 5° uphill slopes, and 5° downhill slopes. Kinematic and kinetic data were collected, and a launch monitor measured outcomes.	COP changed during the backswing on sloped surfaces, but showed no significant changes during the downswing. Launch angle and ball spin were affected by slopes, but ball speed was not. Uphill shots tended to go left and downhill shots to the right.

Table 2.2. Continued

Study author	Sample	Procedure	Results
Jones et al. (2018)	3 participants with different skill levels	Variability and regularity of ground reaction force trajectories were quantified for iron and driver shots. Pointwise median absolute deviation, sample entropy, and cross-entropy methods were used to assess variability and regularity.	There was no difference in variability magnitude between participants. The structure of this variability differed: the ground reaction force of the most skilled participant was significantly more regular compared with less experienced players. Variability and neuromuscular coordination varied between the different components of ground reaction force. Entropy measures provided additional information on coordination differences during the golf swing.
Jones et al. (2023)	104 amateur golfers	COP trajectories were analyzed in driver and 5-iron shots using discrete and continuous methods. Discrete methods applied different clustering criteria, resulting in two-cluster and twenty-cluster solutions.	The two-cluster solution revealed characteristics of the front-foot and reverse COP styles. Continuous analysis showed that the clusters were not clearly separated, supporting the existence of a multidimensional continuum. Principal components showed a high correlation with handicap and club speed. Low-handicap players with higher swing speed tend to present a front-foot style.
Jones et al. (2024)	104 right-handed amateur players, distributed across three handicap categories: Category 1, <5, n = 31; Category 2, 6-12, n = 35; and Category 3, >13, n = 38.	Experimental study conducted in a laboratory equipped with a motion capture system, Qualisys Oqus 300+, two AMTI force platforms, and TrackMan 3e Doppler radar. Each participant performed between 8 and 14 driver shots and 6 to 18 5-iron shots. Three-dimensional ground reaction forces, GRF, normalized by body weight, were	Lower-handicap players showed lower intraindividual variability in ground reaction forces, particularly in principal components 3 and 5 for the driver and in the first four components for the 5-iron, reflecting greater stability and motor consistency. Differences were significant in six of the ten components, $p < 0.05$. Force variability

Table 2.2. Continued

Study author	Sample	Procedure	Results
		recorded. Principal component analysis, PCA, was used to identify variability patterns and test relationships with handicap level.	decreased with proficiency, suggesting that mechanical stability is an objective indicator of technical progress in golf.
Kevin A. Ball & Russell Best (2011)	46 golfers, professionals, amateurs, and recreational players	Golfers performed 10 swings with each club, driver, 3-iron, and 7-iron, while standing on two force platforms. Golfers' COP position was quantified at eight swing events identified from 200 Hz video. Cluster analysis was used to identify COP patterns.	Two swing styles were identified: front-foot style and reverse style. Most golfers, 96%, maintained the same style across all three clubs. The reverse style positioned the COP closer to the toes at ball contact compared with the front-foot style.
Lindsay et al. (2002)	44 professional golfers, Alberta Professional Golf Association	Trunk movement was analyzed using a triaxial electrogoniometer during the full swing with a driver and a 7-iron. Movement amplitude and velocity were measured in the sagittal, frontal, and transverse planes.	During the swing, greater maximum flexion and left lateral bending amplitude were observed with the 7-iron. Maximum right lateral bending velocity was also higher with the 7-iron. Differences in club length and ball position affected swing mechanics and trunk/spine movement. The 7-iron emphasized lateral trunk movement more than the driver.
Lynn & Noffal (2010)	7 collegiate golfers, male and female	Analysis of frontal-plane knee moments during the golf swing in two foot positions, straight and externally rotated, using a three-dimensional linked-segment model. Knee force moments were compared with athletic maneuvers and daily activities.	The externally rotated, EXT, foot position reduced peak knee adduction force moment compared with the straight, STR, position, but had no effect on the abduction force moment. Knee adduction moments during the golf swing were similar to those observed in jump landings, but lower than in side-cutting movements. Knee force moments during the golf swing may contribute to the

Table 2.2. Continued

Study author	Sample	Procedure	Results
			development of pathologies, and swing modifications and compensatory exercises may help reduce these loads.
Marshall and Llewellyn (2017)	10 collegiate golfers, 5 men and 5 women; mean age 19.2 years; handicap 2-22	Range of motion, ROM, flexibility, Sit and Reach, Thomas, and Scratch Tests, and balance, BESS Test, were assessed. Each golfer performed 10 shots with their own driver on an Optishot simulator to measure clubhead speed and total shot distance.	Better balance, fewer errors on the BESS Test, correlated with greater mean drive distance in men, $r = -0.850$, $p = 0.034$. Negative trends were also observed between flexibility and swing performance. Incorporating balance and flexibility exercises into training is recommended to improve golf performance.
McNally et al. (2014)	36 male adults with varied skill levels	A passive optical motion capture system based on reflective markers was used together with force platforms to calculate mechanical work of the lower limbs during the downswing phase.	Total lower-limb work was a strong predictor of clubhead speed, suggesting the importance of the kinetic contribution of the lower limbs to golf performance.
Mears et al. (2018)	22 right-handed low-handicap golfers, age 26 ± 7 years	Principal component analysis, PCA, fuzzy coding, and multiple correspondence analysis, MCA, were used to investigate movement patterns in low-handicap golfers. Data on thoracic and pelvic axial rotation, center of pressure, COP, and center of gravity, COG, were captured during golf swings. Club and ball speeds were measured as supplementary impact parameters.	Results showed that thoracic and pelvic axial rotation patterns explain variations in magnitude, rate of change, and timing throughout the swing. MCA identified relationships between movement patterns and impact parameters, such as club and ball speed. Players with greater axial rotation during the backswing phase tended to perform better.
Navarro et al. (2022)	55 golfers of different skill levels	The study compared pressure distribution patterns in baropodometric insoles during driver and 5-iron swings, using ultrathin insole sensors, 4 sensors/cm ² , at a frequency of 100 Hz. Five swings per club were selected,	Significant differences were found in pressure distribution patterns between the left and right feet for both clubs. The pressure pattern remained similar when changing from the 5-iron to the driver. Differences were

Table 2.2. Continued

Study author	Sample	Procedure	Results
		with the sensors divided into seven areas for pressure analysis.	observed between the patterns of professional players and those with medium and high handicaps. The observed pattern is consistent with the principle of weight transfer, with distinct behaviors in medial and lateral foot areas.
Odabaş et al. (2019)	8 golfers from the Turkish National Team, 3 women and 5 men	Static and dynamic biomechanical assessment of posture, with plantar pressure distribution analysis using the DBIS, Dynamic Balance and Information System, and an electronic modular baropodometric test.	Differences were observed in contact surface and loading between forefoot and rearfoot, as well as in weight distribution between the feet. Differences were found between the dominant and non-dominant foot. Balance performance indices, BPI, showed high values: Static BPI = 27 points; Dynamic BPI = 29 points; Stabilometric Assessment = 20 points, corresponding to good body stability according to the system scale, 0-100 points.
Pataky (2014)	32 right-handed amateur golfers, age 45.2 ± 13.1 years; handicaps 2.7 to 25	The correlation between maximum in-shoe plantar pressures and clubhead speed during the golf swing was studied. Plantar pressures were recorded at 100 Hz, and club speed was measured with Doppler radar.	A positive correlation was found between lateral plantar pressure on the target-side foot and clubhead speed, suggesting that the location of weight transfer on the target-side foot is as important as the magnitude of that transfer for maximizing club speed in amateur golfers.
Prokopy et al. (2018)	31 professional and high-handicap amateur golfers	Assessment of ground reaction forces, GRFs, during normal/stock trajectory shots, high draw, and low fade using a 6-iron.	Vertical GRFs of the support foot were higher for HD shots and occurred later for LF shots. The AP GRF difference was greater for HD shots. Variation between golfers was wide, with between-golfer differences accounting for 89.9%-93.6% of the total variance.

Table 2.2. Continued

Study author	Sample	Procedure	Results
Severin et al. (2022)	17 older male golfers, 62.2 ± 8.8 years	Kinetic analysis of golf swings using a driver and a 6-iron, with a 10-camera 3D motion capture system and two force platforms. Hip, knee, and ankle joint force moments, ground reaction forces, GRF, and inclination angles between the center of mass, COM, and center of pressure, COP, were calculated.	Significant differences were observed in 3D support moments between the driver and the 6-iron. The driver generated higher clubhead speed, 17% higher, while the 6-iron showed a greater support moment on the lead leg during the follow-through. COM-COP inclination angles varied between clubs, indicating different balance demands.
Sohn & Choi (2013)	7 low-handicap golfers	Five different golf shot power conditions, 70%, 80%, 90%, maximum, and round style, were measured with 10 Vicon cameras, two AMTI force platforms, and the Flightscope, Kudu, analysis system. Ten biomechanical indicators were measured at five events during the golf swing, such as takeaway, top of backswing, mid-downswing, peak GRF in the left foot, and impact. A Self-Organising Map was used to compare the ability to distinguish between individuals.	The study revealed that, although power control is an important aspect, differences between players were more pronounced in terms of individual characteristics than shot power. Variability in shot performance was influenced more by individual biomechanical characteristics than by controlled power. Individual performance variability was significant, especially among lower-handicap golfers.
Stokes et al. (2023)	16 right-handed amateur golfers	Kinematic and kinetic analysis of the lead knee in two stances, square and open, and with four club types, driver, 3-iron, 6-iron, and 9-iron. Data collection was performed using two force platforms and a 3D motion capture system.	The open stance reduced most lead-knee translations, rotations, forces, and force moments across all four club types compared with the square stance. The open stance reduced rotation, -28%, compressive force, -5%, and rotation force moment, -9%. The driver showed significantly higher values compared with the other clubs.

Table 2.2. Continued

Study author	Sample	Procedure	Results
Takagi et al. (2021)	31 right-handed experienced golfers, handicap 3.5 ± 1.8	Players performed driver swings. Kinematic and kinetic data were collected using a 3D optical motion analysis system and two force platforms. Dynamic factors, joint force moment, gravitational force, motion-dependent forces, and inertial forces, contributing to axial angular acceleration of the hip were calculated.	Flexion and adduction force moments of the left, lead, hip and extension and abduction force moments of the right, support, hip were identified as the main contributors to axial angular velocity of the hip. These force moments did not contribute synchronously, but sequentially. Knee force moments, which contributed little directly to axial angular velocity of the hip, may support the generation of large hip force moments by regulating joint postures. Functional coordination of lower-limb segments and the magnitude of joint force moments play an important role in hip rotation.
Wells et al. (2020)	50 highly skilled right-handed male golfers, handicap ≤ 5 ; mean age 20 ± 1.8 years	Vertical ground reaction force, vGRF, asymmetry was assessed in tasks such as countermovement jumps, CMJ, squat jump, SJ, drop jump, DJ, and isometric mid-thigh pull, IMTP. Clubhead velocity, CHV, was measured using TrackMan 3e, and asymmetries were analyzed to determine their relationship with CHV.	There was no significant relationship between vGRF asymmetries and CHV, $r = -0.14$ to 0.22 . Asymmetries varied between individuals and tasks. Asymmetries are inherently individual and task-dependent, so it is recommended to focus on interventions that directly increase CHV, such as strength and plyometric training.

2.3.3. Performance Parameters

The effectiveness of the golf swing and shot performance result from the interaction between multiple biomechanical factors, including clubhead speed, joint rotation, force distribution, and the characteristics of ball impact.

Unlike the previous sections, which addressed the mechanisms of movement coordination and control, this section focuses on objective performance indicators, analyzing how kinematic and kinetic variables relate to shot effectiveness. Parameters such as ball and clubhead speed, carry distance and accuracy, launch angle and ball spin, as well as the distribution and timing of ground reaction forces, are considered.

The aim is to understand which of these biomechanical markers are most determinant for performance and how they vary according to skill level, sex, club type, and individual player characteristics (Table 2.3).

2.3.3.1. Swing speed and effectiveness

Rusdiana et al. (2023) identified that experienced players have higher club speed at impact, lower lateral ball deviation, and greater shoulder rotation compared with amateurs. These factors reflect a more efficient movement sequence, highlighting the importance of harmonizing lower-body rotation with the swing to maximize ball speed. Mackenzie et al. (2018) analyzed the influence of club shaft deflection and found that high-torque shafts were associated with greater delivered loft and a more open face at impact, resulting in a final ball position farther to the right. Club shaft deformation should therefore be considered when selecting equipment for players of different levels. In addition, variations in shaft stiffness and flexion profile influence the timing of energy release during the downswing, affecting clubhead speed and control of ball trajectory.

Regarding the practitioner's biomechanical factors, Brown et al. (2011) explored biomechanical factors influencing clubhead speed and found that a greater pelvis-thorax differential at the top of the backswing and greater trunk flexibility were correlated with increased club speed. In addition, grip strength of the lead upper-limb hand showed a significant correlation with clubhead speed, highlighting the importance of grip stability. Egret et al. (2006) compared male and female players and identified that women showed a wider swing, with greater hip and shoulder rotation angles at the top of the backswing, whereas men flexed the lead lower-limb knee more during this phase. However, no

significant differences in club speed were observed between sexes, suggesting that both may adopt different biomechanical strategies to achieve similar performance levels.

2.3.3.2. Applied force, force moment, and technical individuality

Choi and Park (2020) analyzed in 3D the forces applied by the hands during the swing and found that the force moment generated by the right hand was approximately three times greater than that of the left hand. In addition, force peaks in the lead upper limb occurred before those in the trail upper limb, suggesting that stabilization and power generation begin on the lead side before club acceleration. E. Komi et al. (2007) reinforced the individuality of the force applied, finding that each golfer has a unique and repeatable grip-force signature, which varies between players of different skill levels. Todd et al. (2020) compared full and partial swings and found that the partial swing was not simply a reduced version of the full swing. Body movement was reduced by 33% in the center of pressure migration area and by 25% in lateral displacement, whereas trunk rotation showed a smaller decrease, 14%, indicating that partial swings may require distinct technical adjustments to maintain shot consistency and accuracy.

2.3.3.3. Segmental control and joint influence

Fedorcik et al. (2012) identified that high-handicap players showed greater radial wrist variation at the end of the backswing and at ball contact, as well as a steeper downswing angle when the upper forearm was parallel to the ground. These biomechanical characteristics may compromise impact accuracy, suggesting that less experienced players may require adjustments in wrist control to increase shot stability and effectiveness. Somjarod et al. (2011) analyzed knee movement and found that professional players showed significant differences in lead lower-limb flexion angle at impact and during the follow-through compared with amateurs. External rotation of the lead lower limb was also more pronounced in high-level players, indicating that knee joint adjustment may be a key factor in optimizing swing power and control. Gatt et al. (1998) studied the influence of footwear on knee kinetics and found that forces and peak knee force moments varied between the lead and trail lower limbs, but were not significantly affected by footwear type, with or without spikes. However, maximum knee loads during the swing were comparable to those observed in activities restricted until advanced knee rehabilitation, highlighting the mechanical stress experienced by this joint during the shot.

2.3.3.4. Stability, coordination, and consistency

Brouwer et al. (2021) compared the accuracy of 3D trunk orientation measurements using inertial measurement units and an optoelectronic motion capture system, the gold standard. The results indicated that angular differences between the two methods were below 5 degrees and showed high correlation, $R \geq 0.90$, demonstrating that inertial measurement units are a viable alternative for field measurements. Lamb et al. (2011) used artificial neural networks to analyze interlimb coordination during chip shots at different distances. Nonlinear phase transitions were observed for three of the four players analyzed, highlighting the usefulness of these tools for understanding stability and variations in movement patterns.

Speariett and Armstrong (2020) demonstrated that there is a significant correlation between composite scores on the Golf-Specific Functional Movement Screen, GSFMS, and performance variables such as clubhead speed, ball speed, and pelvic rotation. The most challenging tests included single-leg balance, deep squat, and pelvic tilt. In addition, common swing faults were identified, such as altered postural alignment, slide, and early hip extension.

Skibski et al. (2025) demonstrated that a brief dynamic warm-up significantly improves Titleist Performance Institute screen scores in adults, with immediate gains in mobility, stability, and coordination after the warm-up. These results indicate that warm-up status influences functional assessments and should be controlled when interpreting relationships between movement tests and performance variables.

2.3.3.5. Strength, power, and performance prediction

Donahue et al. (2021) identified that grip strength shows a significant positive correlation with clubhead speed, ball speed, and carry distance, suggesting that strengthening manual grip strength may be a determining factor in performance. Read et al. (2013) found that explosive power, measured through rotational throw and seated medicine ball throw, as well as depth jump, were the strongest predictors of clubhead speed, explaining 49% of the variance, highlighting the importance of rotational strength and lower-limb power in maximizing clubhead speed.

Wells et al. (2024) analyzed the relationship between countermovement jump kinetic variables and clubhead speed in highly skilled players. Positive impulse and net impulse showed the strongest correlations with clubhead speed, outperforming mean and peak power, peak force, and force at zero velocity. Jump height was not significantly

associated, reinforcing that the ability to apply force over time is more determinant for swing performance than the height achieved in the jump.

In DP World Tour professionals, Bage et al. (2024) found that positive impulse and net impulse in the countermovement jump robustly predict mean drive distance. Regression models explained up to approximately one third of the variance in distance, whereas maximal isometric strength in the mid-thigh pull did not add substantial predictive value to the models. These results highlight the relevance of the temporal profile of vertical force application for drive performance at the highest level.

In high-level amateurs, Brennan et al. (2024) observed strong to very strong correlations between maximal strength and power, assessed by isometric mid-thigh pull, isometric bench press, and countermovement jump, and performance indicators with the driver and 6-iron, namely clubhead speed, ball speed, and carry distance. Countermovement jump impulse was consistently associated with all shot metrics, whereas thoracic rotation showed moderate correlations. Group analysis indicated that athletes with greater strength and power show higher values of clubhead speed, ball speed, and carry distance, without relevant differences in smash factor.

In elite amateur female players, Robinson, Murray, Coughlan, et al. (2024) identified that clubhead speed is more strongly associated with markers of rapid force production, namely force at one hundred and two hundred milliseconds in the bench press and mid-thigh pull, and positive impulse in the countermovement jump. Athletes with greater force production in the first two hundred milliseconds showed higher clubhead and ball speeds and greater flight distances. Thoracic mobility did not show significant correlations, suggesting that rapid force production is more determinant than maximal strength or mobility when analyzed in isolation in relation to swing performance.

In professional players from the Ladies European Tour, Robinson, Murray, Glover, et al. (2024) reported that the countermovement jump, particularly positive impulse, showed the strongest and most consistent associations with clubhead speed and flight distance. Force at one hundred milliseconds in the mid-thigh pull was highly correlated with carry distance, reinforcing the importance of the ability to generate force rapidly in the lower limbs for drive performance. Upper-limb isometric strength showed only moderate correlations.

2.3.3.6. Individual differences and specific biomechanical factors

Parker et al. (2022) compared elite male and female players and confirmed trends previously described in the literature, finding that women showed lower values of clubhead speed and carry distance. In addition, kinematic variables such as time to peak upper-limb velocity during the downswing and wrist angular velocity were slower in women, suggesting that performance differences may be associated with specific biomechanical factors and not only with muscle strength.

Horan et al. (2014) analyzed the influence of prolonged putting practice on trunk and pelvis movements and found that female players showed a greater impact on segmental orientation and velocities than male players. Women demonstrated lower anteroposterior pelvic tilt and lower axial rotation of the thorax and pelvis, both before and after practice.

Robin M. Queen et al. (2013) investigated the transfer of vertical force from the trail foot to the lead foot and found that low-handicap players generated greater vertical, lateral, and medial forces earlier in the swing than high-handicap players. This anticipation in weight transfer may contribute to greater efficiency in power generation. On the other hand, Meister et al. (2011) demonstrated that professional players showed greater consistency in variables such as the X-factor and S-factor, which are fundamental for efficient trunk and pelvic rotation. Amateurs, by contrast, showed more pronounced deviations in swing execution, reflecting lower motor control and lower efficiency in generating club speed at impact.

2.3.3.7. Consistency, motor control, and technological innovation

Zhang and Shan (2014) analyzed 19 biomechanical parameters and identified that 14 of them are sensitive to variation in motor control. Among the main areas affected by inconsistency were ball position, club angle, movement transition, wrist control, and posture. The analysis suggests that corrections in these areas may improve swing consistency and shot performance. Myers et al. (2008) confirmed the importance of thorax-pelvis separation in increasing ball speed, highlighting that greater rotation and separation velocity of the upper trunk during the downswing are associated with better energy transmission to the ball. Harper et al. (2008) used an advanced swing robot, Robo5, to replicate different swing profiles of players at various levels. The study demonstrated that, with appropriate corrections, it is possible to customize golf equipment to optimize performance based on each player's individual style.

Wu et al. (2019) developed a multifunctional sensor based on triboelectric nanogenerators to measure swing force and acceleration. The device was effective in detecting club-ball impact, allowing more detailed performance analysis. Conversely, Matsumoto et al. (2016) analyzed the influence of club inertia on shaft deflection and concluded that heavier clubs showed greater deflection and distinct velocity patterns, suggesting that optimal club selection should take into account the relationship between moment of inertia and player characteristics. Zhao et al. (2023) analyzed 3D motion capture data from athletes in several sports, including golf, and provided information on mobility, stability, and power. The analysis allows movement patterns to be identified and more effective training protocols to be developed to maximize performance and reduce injury risk.

Together, these studies reveal that golf performance depends on a complex combination of explosive strength, segmental coordination, and refined motor control.

The ability to generate force rapidly and in a coordinated manner, combined with postural stability and technical precision, distinguishes elite players from amateurs. Technological advances in biomechanical instrumentation and analysis, including portable sensors and artificial intelligence methods, have made it possible to identify specific performance patterns and adapt training and equipment to each athlete's individual characteristics, promoting an increasingly scientific and personalized approach to golf performance.

Table 2.3. Characteristics of the selected studies addressing analysis of performance parameters.

Study author	Sample	Procedure	Results
Bage et al. (2024)	25 male professional players from the DP World Tour, with a mean age of 30.0 ± 5.3 years, height of 1.82 ± 0.07 m, body mass of 82.2 ± 7.0 kg, and approximately 9 years of professional experience.	Cross-sectional correlational study. Athletes performed countermovement jumps, CMJ, and isometric mid-thigh pulls, IMTP, on PASCO force platforms, 1000 Hz. Kinetic variables such as positive impulse, PI, and net impulse, NI, from the CMJ, as well as maximal and partial force, 200-300 ms, from the IMTP, were analyzed. Mean driving distances were obtained from the official DP World Tour ShotTracker.	Positive impulse, $r = 0.461$; $p = 0.01$, and net impulse, $r = 0.431$; $p = 0.016$, were significantly correlated with driving distance. The model including PI and NI explained 27.8% of the variance in distance, $p = 0.028$, while the inclusion of force at 250 ms increased the explained variance to 32.8%. It was concluded that jump impulse variables are strong predictors of driving distance, highlighting the importance of efficient vertical force application. Explosive power training should be prioritized to optimize mechanical impulse and performance.
Brennan et al. (2024)	26 high-level amateur players, 22 men and 4 women, with a mean age of 19.1 ± 5.9 years, height of 177 ± 7.2 cm, body mass of 77.4 ± 12.5 kg, and mean handicap of 4.98 ± 4.29 . All had at least four years of competitive experience.	Cross-sectional experimental study. Maximal strength and power were assessed through the isometric mid-thigh pull, IMTP, isometric bench press, countermovement jump, CMJ, seated medicine ball throw, and thoracic rotation. Golf performance was measured with FlightScope Mevo+, validated with TrackMan, in driver and 6-iron shots, analyzing clubhead speed, CHS, ball speed, carry distance, and smash factor.	Maximal strength and power correlated strongly with performance, $r = 0.46-0.82$. The isometric bench press was the main predictor of CHS and ball speed, r up to 0.76. IMTP correlated with distance and ball speed, $r = 0.61-0.65$. Stronger and more powerful players showed greater gains in CHS, ball speed, and distance, +1.1 to +1.5 ES. Thoracic mobility showed moderate correlations. It was concluded that performance depends mainly on explosive strength and power of the lower

Table 2.3. Continued

Study author	Sample	Procedure	Results
			limbs and maximal strength of the upper limbs, with thoracic mobility acting as a complementary factor.
Brouwer et al. (2021)	10 participants, who performed 71 dynamic sport movements and 125 anatomical trunk movements.	The accuracy of three-dimensional trunk orientation measurement using inertial measurement units, IMUs, was compared with an optoelectronic motion capture system, the gold standard. Movements included golf swings, ball throws, tennis serves, and baseball swings.	Angular differences between the IMU and the optoelectronic capture system were below 5 degrees, with high similarity, $R \geq 0.90$, for dynamic sport movements, showing that IMUs are a promising alternative for field measurements.
Brown et al. (2011)	16 low-handicap female golfers.	3D motion capture with 12 stereoscopic cameras and a launch monitor system to collect ball-flight parameters. Analysis of covariance was performed to determine the relationship between swing characteristics and performance.	Swing characteristics associated with clubhead speed included increased pelvis-thorax differential at the top of the backswing, greater pelvic translation during the backswing, and reduced absolute backswing time. Significant correlations were found between lead-hand grip strength and clubhead speed, and between handicap and clubhead speed. Flexibility measures showed a positive correlation with clubhead speed, seated flexibility clockwise and counterclockwise. There is no single swing technique for optimal performance in low-handicap female golfers.
Choi and Park (2020)	9 registered professional golfers.	Direct measurement of 3D grip force using an instrumented grip. Participants completed two sets of data collection with regular and customized grips.	Torque application with the trail upper-limb hand was three times greater than that of the lead upper-limb hand. Force and joint moment of the lead upper limb tended to precede those of the trail upper limb, with peaks around impact and higher magnitudes. The heuristic estimate

Table 2.3. Continued

Study author	Sample	Procedure	Results
			based on club kinematics showed a reasonable approximation.
Donahue et al. (2021)	14 Division I collegiate golfers.	Golfers performed a battery of physical tests, including vertical jump, grip strength, rotational medicine ball throw, and sit-and-reach flexibility test, in addition to anthropometric measures. Golf-specific variables included clubhead speed, CHS, ball velocity, BV, and carry distance, CD, measured with the participants' driver.	Significant positive correlations were found between grip strength and all golf-specific variables, CHS, BV, and CD. Height also showed a significant positive correlation with CHS and BV. The association between anthropometric and physical performance measures and golf-specific variables was limited, except for grip strength.
Egret et al. (2006)	7 male and 5 female golfers.	Kinematic analysis of the golf swing was performed using a VICON optoelectronic system, Oxford Metrics, with five cameras at 50 Hz. Club speed was measured with radar.	Women showed a wider swing with greater hip and shoulder rotation angles at the top of the backswing. Men flexed the lead lower-limb knee more during the backswing. No significant differences in club speed were found between sexes.
Fedorcik et al. (2012)	28 golfers, 15 low-handicap and 13 high-handicap.	Wrist mechanics were analyzed using an eight-camera 3D motion capture system. Radial wrist deviation and club descent angle were measured.	High-handicap golfers showed greater radial wrist deviation at the end of the backswing and at ball contact, as well as a greater descent angle when the upper forearm was parallel to the ground, compared with low-handicap golfers.
Gatt et al. (1998)	13 golfers.	Analysis of knee kinetics during the golf swing with two types of footwear, with and without spikes. A 3D motion capture system and force platforms were used to record kinetic variables.	Forces and peak knee moments differed significantly between the lead knee and support knee, but were not significantly affected by footwear type. Lead-knee flexion and internal rotation moments were significantly

Table 2.3. Continued

Study author	Sample	Procedure	Results
			correlated with skill level. Some peak knee loads during the swing approached those observed in activities restricted until advanced knee rehabilitation. The most stressful phase for the knee during the swing is the downswing, and each golfer appears to have consistent knee-loading patterns.
Harper et al. (2008)	1 traditional swing robot, Robo3, 1 advanced swing robot, Robo5, and golfers in 4 skill categories: professional, Category 1, handicap < 5, Category 2, handicap 6-12, and Category 3, handicap 13-20.	A 3D kinematic study was performed using the Codamotion system to measure and analyze golfers' joint angles and swing profiles. The advanced robot, Robo5, was modified with new control algorithms that allowed replication of variable swing profiles. Cubic fitting curves were used to generate commands for the robot.	The traditional robot showed limited ability to represent human swings because it was restricted to a single profile. With the modifications, Robo5 replicated the swings of different golfers with high accuracy and consistency. The study demonstrated the feasibility of customizing golf equipment based on each player's individual style.
Horan et al. (2014)	19 male golfers, age 26 ± 7 years; handicap 0.6 ± 1.1 , and 17 female golfers, age 24 ± 7 years; handicap 1.4 ± 1.7 .	Three-dimensional kinematic data of the trunk were collected during full swings before and after 40 minutes of putting practice. Angular displacement angles of the thorax and pelvis were calculated at three points, address, top of the backswing, and ball contact, in addition to maximum angular velocity and repeatability of segmental angular velocities.	Female players showed lower anteroposterior pelvic and thoracic tilt at address, lower axial rotation of the thorax and pelvis-thorax interaction at the top of the backswing, and lower axial pelvic rotation and lateral tilt at ball contact, both before and after putting. Maximum angular velocity of pelvis-thorax lateral tilt was significantly lower in women after practice. Prolonged putting practice affected orientation kinematics and velocities more in female than in male players.

Table 2.3. Continued

Study author	Sample	Procedure	Results
Komi et al. (2007)	20 golfers of varied performance levels.	Grip force during a tee shot was measured using two methods: a thin-film sensor applied to the club and 31 individual sensors in gloves to measure pressure in specific hand regions. High-speed video was recorded to identify key swing phases.	Each golfer showed a unique and repeatable grip-force signature, which varied between golfers.
Lamb et al. (2011)	4 golfers of different skill levels.	Analysis of intersegmental coordination during chip shots using artificial neural networks, specifically self-organizing maps, SOMs. Shots at six different distances were analyzed.	Trajectories of corresponding nodes in the SOM showed changes in coordination between movement patterns for short and long chip shots. Attractor diagrams showed nonlinear phase transitions for 3 of the 4 players. The study highlighted the usefulness of SOMs for visualizing coordination stability and phase transitions in movement.
Mackenzie et al. (2018)	40 right-handed golfers of different skill levels.	A 3D optoelectronic motion capture system was used to collect shaft deflection, club and handle kinematics, and Doppler monitor data for ball flight.	The high-torque shaft, HT, was associated with increased delivered loft and a more open face compared with the low-torque shaft, LT, resulting in a final ball position farther to the right for HT. The face-angle change due to shaft deformation was significantly greater for HT in 25 of the 40 participants.
Matsumoto et al. (2016)	Golfers who used golf clubs with different inertia and flexibility characteristics.	Experimental investigation of the impact of club inertia on shaft movement during the swing. Sensors captured data on shaft deflection and moment in the club shaft, correlating results with different inertia configurations	Club inertia significantly affected shaft movement, with heavier clubs showing greater deflection and different velocity patterns. The results suggest that selecting the optimal club inertia may improve accuracy and

Table 2.3. Continued

Study author	Sample	Procedure	Results
		and physical club characteristics, such as moment of inertia and elastic modulus.	performance by aligning equipment characteristics with the golfer's style and ability.
Meister et al. (2011)	10 male professional golfers and 5 male amateurs.	Three-dimensional kinematic and kinetic analysis, including upper torso rotation, pelvic rotation, X-factor, stretch factor, correlated with club speed at impact, CSI.	High consistency among professionals was observed in free moment, X-factor, and S-factor variables. The downswing began with reversal of the pelvis and torso. X-factor at impact and upper torso rotation correlated with club speed at impact. Amateurs showed greater deviations from professionals in these variables.
Myers et al. (2008)	100 recreational golfers.	Players underwent biomechanical analysis of the golf swing using their own driver. Upper trunk and pelvic rotation and velocity, torso-pelvis separation, and torso-pelvis separation velocity were measured for each swing. Ball speed was assessed with a golf launch monitor.	Significant differences were observed between groups based on ball speed, and moderate correlations were found between increased ball speed and maximum trunk-pelvis separation at the top of the swing. Upper trunk rotational velocity when the lead upper limb was parallel to the ground, and trunk-pelvis separation velocity in the 40 ms before impact, showed a direct relationship with ball speed. Trunk-pelvis separation contributed to greater angular velocity of the trunk and pelvis during the downswing, resulting in higher impact speed.
Parker et al. (2022)	20 elite golfers, 10 female and 10 male.	Collection of swing kinematics and driver performance data. Comparison between sexes.	CHS and carry distance were lower in women compared with men. Kinematic variables such as time to peak upper-limb velocity during the downswing and wrist angular velocity were lower in women. ANCOVA

Table 2.3. Continued

Study author	Sample	Procedure	Results
			identified participant as a fixed factor determining CHS, but not carry distance.
Queen et al. (2013)	28 male golfers, divided into low-handicap < 9 and high-handicap > 9 groups.	Analysis of ground reaction forces, GRF, and the timing of peak weight transfer during the golf swing. Vertical, lateral, and medial GRFs were measured bilaterally using a force platform in three swing phases: address to top of backswing, top of backswing to ball contact, and ball contact to the end of follow-through.	The low-handicap group, LHCP, showed greater vertical force transfer from the trail foot to the lead foot in phase 2 than the high-handicap group, HHCP. The LHCP group also showed earlier peak vertical force timing throughout the swing, as well as earlier lateral and medial force peaks in phases 1 and 2. LHCP golfers generated greater forces earlier than HHCP golfers.
Read et al. (2013)	48 male golfers, age 20.1 ± 3.2 years; handicap 5.8 ± 2.2 .	The following variables were assessed: anthropometry, squat jump height, SJ, and squat jump peak power, SJPP, unilateral countermovement jump heights, right and left, bilateral countermovement jump heights, countermovement jump peak power, CMJPP, seated medicine ball throw, MBST, and rotational medicine ball throw, MBRT.	Significant moderate correlations were found between CHS and MBRT, MBST, CMJPP, and SJPP. Significant weak correlations were found between CHS and other variables, excluding LLCMJ. Multiple regression analysis identified MBST and SJ as the strongest predictors of CHS, explaining 49% of the variance. Intraclass correlation coefficients were acceptable. Concentrically dominant movements showed stronger relationships with CHS.
Robinson et al. (2024a)	19 elite amateur female players, Category 1 or better, mean age 16.3 ± 1.3 years, height 166.3 ± 3.6 cm, body mass 64.0 ± 11.3 kg, and mean handicap $+1.45 \pm 0.7$. All had ≥ 3 years	Single 90-minute session at a national performance center. Driver data, clubhead speed, ball speed, flight distance, and smash factor, were collected with TrackMan 4. Thoracic rotation, countermovement jump, CMJ, isometric bench press, and isometric mid-	CHS showed moderate to strong correlations with force at 100 ms in the bench press, $r = 0.70$, force at 200 ms in the IMTP, $r = 0.62$, and positive impulse in the CMJ, $r = 0.61$. The group with greater force at 200 ms showed higher CHS, $+1.13$ g, ball speed, $+0.90$ g, and distance,

Table 2.3. Continued

Study author	Sample	Procedure	Results
	of competitive experience and ≥ 12 months of strength training.	thigh pull, IMTP, were assessed, with three valid trials per test.	+1.01 g, $p < 0.05$. Explosive strength of the lower and upper limbs proved determinant for performance, while thoracic mobility was not significant. It was concluded that the ability to generate force rapidly, <300 ms, is more relevant than maximal strength for increasing club and ball speed.
Robinson et al. (2024b)	19 professional players from the Ladies European Tour, LET, mean age 31.0 ± 5.6 years, height 170.8 ± 7.2 cm, body mass 67.7 ± 9.2 kg, and at least 3 consecutive years of professional experience.	Cross-sectional correlational study conducted during the KPMG Irish Open, LET 2024. Performance data were collected with TrackMan 4, CHS, ball speed, flight distance, and smash factor. Physical tests included CMJ, IMTP, isometric bench press, seated thoracic rotation, and medicine ball throw. Pearson correlations and median split analysis were used for positive impulse in the CMJ.	CMJ showed the strongest correlations with driving performance, $r = 0.51-0.60$. Positive impulse in the CMJ was the best predictor of flight distance and club speed. Force at 100 ms in the IMTP was strongly correlated with distance, $r = 0.59$. Players with greater positive impulse showed higher mean CHS, +0.72 ES, ball speed, +0.79 ES, and distance, +0.80 ES. Correlations with upper-limb isometric strength were only moderate. It was concluded that power and rapid force production in the lower limbs are determinant for competitive success in professional women's golf.
Rusdiana et al. (2023)	12 male players, 6 experienced and 6 amateurs.	3D biomechanical analysis to compare long-distance swing movement and ball speed between experienced and amateur players. Ten kinematic variables were analyzed using a mean difference test to assess results.	Four variables showed significant differences: club speed at impact, lateral ball deviation after impact, shoulder rotation, and non-dominant elbow flexion. Harmonizing the lower-limb movement sequence in the swing is fundamental for maximizing ball speed. Hip

Table 2.3. Continued

Study author	Sample	Procedure	Results
			rotational velocity and shoulder angular velocity are characteristics of professional athletes.
Skibski et al. (2025)	24 adult players, 19 men and 5 women, mean age 44.0 ± 15.4 years, height 171.3 ± 8.6 cm, body mass 82.5 ± 16.3 kg, and mean score of 90.7 ± 10.3 strokes per 18 holes, recreational to intermediate level.	Single-session crossover laboratory study. Each participant completed the Titleist Performance Institute, TPI, screen, composed of 15 tests of mobility, stability, coordination, and motor control. After a rest and washout period, they completed a brief dynamic warm-up with exercises for the upper limbs, lower limbs, and trunk, followed by 30 seconds of practice swings. The TPI was repeated immediately after warm-up. Scores were compared before and after using the Wilcoxon test, $p \leq 0.05$, and effect size, r .	Total TPI scores increased significantly after warm-up, median 36, IQR 31-40, compared with baseline, median 33, IQR 28-36, $p < 0.001$; $r = 0.81$, large effect. Consistent improvements were observed in individual tests, reflecting greater mobility, stability, and overall motor coordination. It was concluded that a short dynamic warm-up significantly improves performance in functional movement assessments, and warm-up status should be considered when interpreting biomechanical and performance results.
Somjarod et al. (2011)	30 golfers, professionals and amateurs.	Players performed three golf swings, recorded with digital video cameras for kinematic analysis of knee movement. The analysis focused on lead lower-limb knee flexion angle and external rotation of the lead and trail lower-limb knees.	Significant differences were found in lead lower-limb knee flexion angle at impact and mid-follow-through between professionals and amateurs. External rotation of the lead lower-limb knee was significant in both groups. No significant differences were found for the trail lower-limb knee.
Speariett and Armstrong (2020)	11 amateur golfers, 5 male and 6 female.	Assessment of the Golf-Specific Functional Movement Screen, GSFMS, and golf performance variables, including handicap, clubhead speed, lateral accuracy, ball speed, pelvic rotational velocity, swing sequence, and common swing faults.	Significant relationships were found between GSFMS composite scores and handicap, clubhead speed, ball speed, and pelvic rotational velocity. The most difficult tests were single-leg balance, deep squat, and pelvic tilt.

Table 2.3. Continued

Study author	Sample	Procedure	Results
			Common errors identified included loss of ideal posture, slide, scapular winging, and early hip extension.
Todd et al. (2020)	13 male golfers.	Biomechanical comparison between full and partial swings. Club, ball, kinematic, and kinetic parameters were measured. A repeated-measures design was used, with at least 10 swings under full- and partial-swing conditions.	Significant reductions were found in body movement, 33.0% in lower-limb pressure area, and lower lateral displacement, 25.5%. Smaller reductions were observed in trunk rotation, 14.1%. The partial swing was not a scaled-down version of the full swing.
Wells et al. (2024)	50 right-handed male Category 1 players, handicap ≤ 5.4 ; mean 2.9 ± 1.9 , mean age 20 ± 1.8 years, height 1.81 ± 0.05 m, and body mass 75.5 ± 12.1 kg. All were experienced, approximately 10.5 h/week of practice, and without recent injuries.	Cross-sectional correlational study. Participants performed countermovement jumps, CMJ, on two Kistler force platforms, 2000 Hz, measuring positive and net impulse, mean and peak power, peak force, isometric force, and jump height. After a standardized warm-up, each athlete performed three CMJs and ten driver swings, measured with TrackMan 3e. Pearson correlations, $p \leq 0.05$, assessed the relationship between clubhead velocity, CHV, and kinetic variables.	Strong and significant correlations were found between CHV and all variables except jump height, $p < 0.001$: positive impulse, $r = 0.695$; net impulse, $r = 0.689$; mean power, $r = 0.645$; peak power, $r = 0.656$; peak force, $r = 0.517$; and isometric force, $r = 0.528$. Impulse was the best predictor of club speed, showing that effective force application over time is determinant for performance. It was concluded that the CMJ is a reliable test, $ICC > 0.9$; $CV < 10\%$, for assessing strength and power associated with the swing, with impulse being the most valid indicator for high-level players.
Wu et al. (2019)	Multifunctional sensor based on triboelectric nanogenerators, TENG, integrated into a translational-rotational magnetic mechanism.	The sensor was designed using a low-dissipation magnetic cylinder rotating around a PTFE friction layer. Performance was optimized by varying electrode materials, Ag, Au, ITO, Cu, GaInSn, and the number of interdigitated electrode pairs, IES.	The sensor demonstrated high sensitivity and ability to detect acceleration, force, and rotational parameters. It was effective in measuring boxing punch acceleration, maximum 30 m/s^2 , and impact force and swing angle in golf clubs, force up to 15 N. The best performance was

Table 2.3. Continued

Study author	Sample	Procedure	Results
			observed with Ag electrodes due to lower work function, low resistance, and suitable surface topography. The sensor can also be used in vehicle safety and other robotic applications.
Zhang and Shan (2014)	22 experienced golfers.	Study based on 3D motion capture and full-body biomechanical modeling. Nineteen parameters, 13 angular, 4 temporal, and 2 distance parameters, were analyzed to characterize successful and failed swings. Five critical areas of variation were identified: ball position, club angle, transition, wrist control, and posture.	Fourteen parameters were sensitive to variations in motor control. The areas most affected by inconsistency included ball position, club angle, transition, wrist control, and posture migration between takeaway and impact. Recommendations were provided to improve consistency.
Zhao et al. (2023)	183 athletes, 153 men and 30 women, aged 9-36 years, competing in eight sports, for example baseball, basketball, football, golf, and tennis.	Three-dimensional motion capture data were collected using an eight-camera Raptor-E system operating at 120-480 Hz. Athletes performed a screening protocol composed of 21 specific movements, for example drop jump, trunk rotation, and lunges. Each movement was tracked with 45 retroreflective markers, processed in Visual3D software, and analyzed for kinematics.	The dataset provides detailed 3D motion capture information on mobility, stability, and power, and is useful for identifying movement patterns, injury risks, and performance metrics. Differences in movement quality across demographic groups and sport levels can be analyzed, helping to develop objective screening and training protocols.

2.3.4. Adaptations and Training Strategies

The studies analyzed in this section show that different training strategies, ranging from motor and biomechanical approaches to specific strengthening and adaptation methods, can significantly influence golf performance (Table 2.4).

2.3.4.1. Motor approaches and learning

Valença et al. (2022) showed that differential learning, compared with guided repetition, produced relevant adaptations in attack angles, clubface angle, and dynamic loft, with improvements in score and clubhead speed at longer distances, 35 to 50 meters. Low-handicap players adjusted the angles more effectively, whereas high-handicap players improved their scores across all distances.

Anisimov et al. (2024) observed, in an intensive longitudinal study with young elite players, increases in carry, +9.2%, ball speed, +7.1%, clubhead speed, +3.5%, and backspin angular velocity, +4.5%, accompanied by a 24% improvement in ball-flight stability. These results suggest that concentrated and integrated training loads, combining warm-up, technical practice, and control games, can generate rapid adaptations that are transferable to the competitive context.

Hasegawa et al. (2019) confirmed that both professional and amateur players adjust their shots according to distance in an individualized way, reinforcing that learning in golf is highly specific and dependent on the ability to adapt to different conditions.

Jin (2025) compared eight weeks of game-based learning, focused on tactical awareness, with traditional technical training. The first type of training led to significant improvements in tactical skills, whereas the second promoted technical gains, namely in drive distance, putting accuracy, and reduced swing variability. The authors advocate an integrated approach combining cognitive and motor training.

In recreational players, Seo et al. (2025) demonstrated that incremental beliefs, centered on learning, increase task orientation, whereas entity beliefs, centered on innate talent, increase ego orientation. Both orientations were associated with greater adherence to practice, suggesting that managing beliefs and goals may strengthen consistent participation in technical and physical programs.

In turn, Gryc et al. (2019) emphasized the importance of temporal stability and lower-limb control for an effective and repeatable swing, suggesting that training should prioritize not only clubhead speed, but also movement consistency.

2.3.4.2. Strength, power, and physical conditioning

The relationship between strength, power, and performance is widely documented. Sorbie et al. (2021) found strong correlations between upper-body power, assessed through Wingate and ballistic bench press tests, and clubhead and ball speed, indicating that the development of explosive strength in the trunk and upper limbs is essential for swing efficiency.

Leary et al. (2012) and Wells et al. (2018) observed significant relationships between vertical force, rate of force development, and clubhead speed. In particular, Wells et al. (2018) showed that peak force and rate of force development in the first 200 milliseconds, assessed through vertical jumps and the isometric mid-thigh pull test, are directly associated with higher clubhead speeds.

Driggers and Sato (2017) found that a resistance training program oriented toward force production in the vertical plane improved muscular power and increased ball speed, carry distance, and total distance.

Macadam et al. (2019) demonstrated that introducing body resistance during the swing resulted in significant increases in clubhead speed and in the vertical and mediolateral forces applied to the ground, suggesting that resisted training may strengthen the base of support and improve movement power.

In post-peak-height-velocity young talents, Shaw et al. (2024) found that 12 weeks of progressive resistance training, performed twice per week, significantly improved maximal strength, power, motor competence, and swing performance, with marked increases in speed and carry distance with both the 6-iron and the driver. These data demonstrate strong neuromuscular transfer to technical performance in adolescents.

Regarding warm-up with weighted clubs, Hébert-Losier and Wardel (2024) observed an immediate increase in clubhead speed, but without improvements in ball speed, suggesting transient mechanical benefits. In continuation, Hébert-Losier and Wardell (2024) reported acute effects in the first set of swings, with increased angular velocity of the trunk, upper limb, and club, and a reduction in downswing time of approximately ten milliseconds. However, smash factor decreased and the effects disappeared in subsequent

sets, indicating an immediate improvement in mechanics, but without sustained power transfer.

In high-level amateur female players, Robinson, Murray, Glover, et al. (2024) documented high adherence to strength and conditioning training, with a particular focus on strength, core, and mobility. The athletes perceived benefits mainly in clubhead speed, distance, and ball speed, although barriers remain related to available time, fatigue, and knowledge gaps concerning the integration of physical training with technical training.

2.3.4.3. Flexibility and mobility

Flexibility and mobility are determinants of swing efficiency, although results vary according to the plane of motion. Joyce (2017a) identified moderate correlations between trunk flexibility in extension and lateral bending and the X-factor, with no significant relationship with axial rotation. Henry et al. (2015) observed that a dynamic warm-up specific to rotation showed no advantages over a placebo warm-up; both increased X-factor stretch, but only temporarily. Langdown et al. (2023) showed that an eight-week strength and flexibility training program improved deep squat mobility, but did not significantly alter swing kinematics, reinforcing the importance of combining physical training and technical practice to ensure effective transfer of physical gains to performance.

2.3.4.4. Coordination, segmental control, and equipment

Coordination between body segments is a determinant factor for consistency and accuracy. Sim et al. (2017) demonstrated that professional players show greater synchronization between the thorax and pelvis in flexion, extension, lateral bending, and rotation movements during the downswing compared with amateurs.

In competitive junior players, Mori et al. (2025) found that a 45-minute Two-Step Swing Drills protocol improved the horizontal and vertical rhythm of the swing, increased ground-player interaction, and raised clubhead speed. Increases of 10 to 20% in angular velocities during the backswing and 3 to 6% during the downswing were recorded, with significant acceleration of wrist release. These short-term effects indicate high practical potential in technical training for junior players.

Regarding equipment, Sorbie et al. (2016) showed that using undersized grips increased clubhead speed without altering upper-limb muscle activation, suggesting that small

modifications may benefit performance. Turner et al. (2020b) and Schorah et al. (2015) found that clubs with a higher moment of inertia reduced swing and ball speed, underlining the importance of balancing power and control when selecting equipment. Faux et al. (2019) demonstrated that prolonged verbal instructions can standardize weight distribution over time, even without immediate changes in club speed or club angle, suggesting that some biomechanical adaptations require prolonged assimilation periods.

2.3.4.5. Technology and technique optimization

The use of technology for technical analysis and correction has shown increasing potential. Huang et al. (2014) developed a system based on Kinect sensors and the Wii Balance Board, capable of identifying postural and weight-distribution errors with more than 80% accuracy, offering real-time feedback, particularly useful for beginner players. Nesbit (2005) used a three-dimensional computational model of the body and club to analyze swing kinematics and kinetics in amateur golfers of different levels, demonstrating that club trajectory, golfer-club interaction forces and torques, mechanical work, and power produced during the downswing vary according to skill level. Nesbit and Serrano, S. Nesbit and M. Serrano (2005), complemented this approach through an energetic analysis of the swing, showing that mechanical efficiency depends on the ability to produce and transfer work and power to the club, as well as on how that energy is converted during the downswing.

From a broader professional development perspective, Roos et al. (2025) identified, among players and coaches, nine fundamental pillars for sustained success: supportive environment, competition-oriented training, career management, multidisciplinary support team, financial resources, physical training, balanced lifestyle habits, psychological and physiological proficiency, and strategic course management. These results reinforce that technical and physical improvement should be integrated into a holistic developmental approach.

In summary, the studies analyzed demonstrate that differential learning and integrated cognitive approaches enhance specific and transferable motor adaptations; strength, power, and neuromuscular stability training improve clubhead speed, ball speed, and kinetic-chain efficiency; flexibility contributes to mobility and injury prevention when associated with technical practice; coordination exercises and equipment adjustments refine segmental control and swing rhythm; and technology provides valuable tools for

assessment, feedback, and training personalization. The integration of these dimensions, adapted to the player's level, age, and competitive context, represents the most promising path to optimize performance and reduce the risk of overload.

Table 2.4. Characteristics of the selected studies addressing training adaptations and intervention strategies.

Study author	Sample	Procedure	Results
Anisimov et al. (2024)	9 players from the Krasny Yar Olympic Reserve School, Russia, undergoing competitive preparation for a tournament against the RNGC SPB Golf Academy team, Saint Petersburg.	Longitudinal experimental study conducted during a 10-day training camp, with approximately 65 hours per week and 210 game actions per day. Each athlete completed three sessions per day, warm-up, technical training, and competitive training. Performance measurements were taken before and after the camp using the GOLFZON Vision Premium simulator, recording variables such as carry distance, ball and clubhead speed, dynamic face angle, and backspin.	After the training camp, significant increases were recorded in all kinematic parameters: carry distance, +9.2%; ball speed, +7.1%; clubhead speed, +3.5%; and backspin angular velocity, +4.5%. Ball trajectory stability improved by 24%, indicating that intensive training promoted consistent gains in swing efficiency and accuracy.
Driggers and Sato (2017)	10 NCAA Division I collegiate golfers.	Participants completed two weekly resistance training sessions, predominantly focused on vertical-axis force exercises, over 10 weeks. Vertical jumps, isometric strength, and golf shot performance were assessed before and after training.	Significant increase in muscular power, countermovement jump, and improvements in golf performance: ball speed, +1.9%; carry distance, +2.1%; and total distance, +1.4%.
Faux et al. (2019)	8 PGA coaches.	Golf coaches performed 5 swings with a 5-iron, captured by a nine-camera motion analysis system synchronized with two force platforms. After a verbal intervention, they performed another 5 swings. One participant underwent a longitudinal case analysis after one year.	Golf performance did not change, namely club speed and club angle at ball impact. The one-year intervention resulted in more even weight distribution at the end of the downswing, indicating greater stability when the center of mass is close to maximum acceleration.

Table 2.4. Continued

Study author	Sample	Procedure	Results
Gryc et al. (2019)	11 elite junior female golfers.	3D motion capture was used to measure lower- and upper-limb movement parameters and clubhead speed. Ten trials were performed with a mid-iron and driver.	A club effect was found at the top of the backswing, shoulder tilt, and at impact, shoulder rotation, shoulder tilt, and clubhead speed. High stability was observed in temporal and lower-limb parameters. Stability of temporal parameters is key for an effective and repeatable swing.
Hasegawa et al. (2019)	10 professional golfers and 10 high-level amateurs.	The study analyzed swing amplitude, impact speed, and the clubhead acceleration profile during practice strokes and actual putting strokes. Regression analyses were conducted to assess how practice strokes reflected subtle differences in putting distances.	The acceleration profile showed that motor control in the practice stroke differed from the actual stroke. Practice strokes were divided into three strategies and five types, suggesting that the purpose of practice strokes varied between golfers. Most players used individual speed criteria to adjust distance. No significant differences were found between professionals and amateurs, but both adopted distance-dependent control strategies.
Hébert-Losier and Wardell (2024)	12 right-handed competitive players, 7 men and 5 women, with a mean age of 22 years and handicap below 3.	Experimental within-subject study comparing two types of warm-up: traditional and weighted-club warm-up, SuperSpeed Golf™. Each participant performed five sets of five driver swings after each protocol, with 3D kinematic analysis and measurements of clubhead speed, angular velocity, and smash factor.	Weighted-club warm-up significantly increased clubhead speed, +2.6 mph, and trunk and limb angular velocities, while reducing downswing time. However, smash factor decreased, indicating lower ball-club impact efficiency. The effects were only temporary, disappearing after the first set of swings. It was concluded that the method momentarily improves

Table 2.4. Continued

Study author	Sample	Procedure	Results
			swing rhythm and speed, but does not generate sustained performance gains.
Henry et al. (2015)	36 amateur golfers, mean age $\pm$ SD: 64 $\pm$ 8 years; 75% men.	Participants were randomly assigned to a rotation-specific dynamic warm-up group, n = 20, or a sham warm-up group, n = 16. X-factor and X-factor stretch were measured before and after warm-up.	There was no significant group $\times$ time interaction for either X-factor or X-factor stretch. Rotation-specific dynamic warm-up did not increase X-factor compared with sham warm-up. Both types of warm-up increased X-factor stretch, but with no significant difference between them.
Huang et al. (2014)	26 beginner golfers.	Golf swing analysis system using the Wii Balance Board and Kinect sensors to detect common posture and center-of-gravity movement errors. Sixty-seven students tested the system to identify the most frequent errors.	The system detected center-of-gravity displacement and posture errors with an accuracy rate above 80%. It provides real-time feedback on swing errors, such as center-of-gravity position and postural errors, helping beginner players improve performance.
Jin (2025)	45 male athletes, aged 18-30 years, randomly divided into three groups: Tactical Awareness Training Group, TATG, Skill-Based Training Group, SBTG, and Active Control Group, ACG.	Eight-week randomized controlled trial designed to assess the impact of game-based training on tactical awareness and technical development in golf. Tactical awareness was assessed using a modified Tactical Skills Inventory for Sport, and technical performance was measured by drive distance, putting accuracy, and swing consistency.	The TATG showed significant improvements in tactical skills, whereas the SBTG improved technical indicators of distance, accuracy, and consistency. The control group showed no relevant changes. Game-based training increased adaptability and decision-making, while traditional technical training improved motor execution. The results suggest that combining cognitive and motor approaches is more effective for optimizing overall golf performance.

Table 2.4. Continued

Study author	Sample	Procedure	Results
Joyce (2017)	15 low-handicap male golfers.	Measurement of trunk flexibility at maximal static range and driver swing kinematics.	Trunk flexibility in extension and lateral bending correlated moderately with the X-factor. Axial rotation flexibility did not correlate. Generalized linear models showed that axial rotation flexibility and swing kinematic variables are associated with higher clubhead speed.
Kim Hébert-Losier and George Leslie Wardell (2021)	12 competitive golfers, handicap < 3.0, mean age 22 ± 6.9 years.	SuperSpeed™ club warm-up was compared with a control warm-up. Each participant completed five sets of five swings, with swing kinematics and body angular velocity data collected.	SuperSpeed™ warm-up increased club speed by 2.6 mph, with smaller and non-significant effects on subsequent shots. There was no significant increase in ball speed.
Langdown et al. (2023)	37 golfers, handicap = 14.8 ± 13.3 , divided into control group, n = 16, and intervention group, n = 21.	The intervention group completed an 8-week strength and flexibility training program, while the control group maintained their normal routines. Pre- and post-intervention assessments were performed for the overhead deep squat, OHS, and 3D swing kinematics with a 6-iron.	Despite significant improvements in hip flexion angle during the OHS in the intervention group, $p < 0.001$, no significant changes were observed in 3D swing kinematics at address, $p = 0.219$, top of the backswing, $p = 0.977$, or impact, $p = 0.994$. OHS variables showed low predictive ability for swing kinematics, $R^2 = 0.109$ to $R^2 = 0.300$. The use of OHS to assess loss of posture in the swing is not recommended, but it may be useful for assessing strength and range of motion.
Leary et al. (2012)	12 recreational golfers, mean age 20.4 years; mean handicap 14.5.	Assessment of force-time curves in the isometric mid-thigh pull, IMTP, vertical jumps, and clubhead speed. Force measures were recorded at 30, 50, 90, 100, 200,	Golf handicap showed a moderate correlation with mean and maximum clubhead speed. Force at 150 ms during the isometric mid-thigh pull test correlated moderately with mean and maximum clubhead speed.

Table 2.4. Continued

Study author	Sample	Procedure	Results
		and 250 ms, as well as rate of force development over the same intervals.	Rate of force development from 0 to 150 ms showed moderate correlations with mean and maximum clubhead speed. The ability to generate high ground reaction forces in less than 200 ms is related to high clubhead speeds.
Macadam et al. (2019)	5 female golfers, 22.0 ± 2.5 years, handicap 4 ± 1.2.	Randomized crossover design. Comparison between shots with and without 1.6 kg body resistance using FlightScope and force platforms.	Body resistance significantly increased clubhead speed, 3.5%, relative vertical forces, 11.4% on the lead side, and relative mediolateral forces, 7.1% on the support side, compared with the unloaded condition. Body resistance improved clubhead speed.
Mori et al. (2025)	10 competitive junior players, 9 boys and 1 girl, mean age 16 years, right-handed and without recent injuries, with mean handicap of 3.	Experimental study with a single 45-minute Two-Step Swing Drills, TSSD, technical training session, composed of four progressive phases: two steps, one step, swing without steps, and transition with ball. Each participant performed seven driver swings before and after the intervention. Data were collected with high-speed cameras and force platforms, analyzing clubhead speed, ground reaction forces, center-of-mass displacements, and segmental angular velocities.	Significant improvements were observed after training: 3% increase in clubhead speed, greater trail-foot impulse during the backswing, and greater lateral and vertical displacement of the body and pelvis. Angular velocities increased by 10-20% during the backswing and up to 6% during the downswing, especially due to increased wrist rotation. It was concluded that TSSD improves swing rhythm and coordination, enabling rapid gains in speed and efficiency even after a single session.
Nesbit and Serrano (2005)	4 amateur golfers, 3 male and 1 female.	Work and power analysis of the golf swing using two computational models to estimate energy production,	The energetic approach provided new information on swing mechanics, identifying the force and moment components that accelerate the club. The detailed

Table 2.4. Continued

Study author	Sample	Procedure	Results
		transfer, and conversion in the body and club during the downswing.	computational club model analyzed energy transfer in the club during the downswing. The whole-body model determined the internal work produced at the joints during the downswing. The results revealed that swing efficiency depends on both force and range of motion for developing clubhead speed.
Nesbit (2005)	84 male and 1 female amateur golfers of various levels.	The study used a variable whole-body computational model and a flexible golf club model. Analyses were based on data from a multicamera motion analysis system.	The golf swing is a coordinated and individual movement. The wrist joints are determinant in generating speed and orienting the clubface. Hand trajectory and the ability to perform work are among the factors most closely related to performance level.
Robinson et al. (2024)	157 high-level amateur female players, handicap up to 10, mostly from the United Kingdom, aged 18-40 years, with 10-14 years of golf practice.	Cross-sectional descriptive study conducted through an online questionnaire composed of four sections: general data, strength and conditioning training practices, perceptions of the impact of physical training on performance, and knowledge and barriers to its application. Data were collected between January and September 2023, with content and frequency analysis of responses.	Most players engaged in regular physical training, especially strength, trunk muscle training, mobility, and power. Players perceived improvements in clubhead speed, flight distance, ball speed, and accuracy. Almost all recognized the role of physical training in performance and injury prevention. The main barriers identified were lack of time, fatigue, and preference for practicing golf. The study concludes that strength and conditioning training is highly valued, but knowledge gaps remain regarding how to integrate it effectively with technical training.

Table 2.4. Continued

Study author	Sample	Procedure	Results
Roos et al. (2025)	17 participants: 15 professional players, 8 men and 7 women, aged 23-41 years, with 4-22 years of competitive experience, and 2 PGA coaches, 1 man and 1 woman, with 37 years of combined experience in technical coaching.	Descriptive qualitative study with semi-structured interviews conducted with professional players and coaches from the Sunshine Tour and the Professional Golfers Association of South Africa. The interviews explored technical, physical, psychological, social, and career management factors related to performance development and maintenance. Analysis followed the reflexive thematic analysis method, with open coding and triangulation of themes.	Nine determining factors for professional success were identified: supportive developmental environment, competitive training, career management, multidisciplinary team, financial resources, physical preparation, balanced lifestyle habits, psychological and physiological proficiency, and strategic course management. The study concluded that sustained success in professional golf depends on a holistic approach integrating technical, physical, psychological, and contextual factors, highlighting the need for a development model adapted to the South African context.
Schorah et al. (2015)	8 golfers, 6 men and 2 women, aged 25.1 ± 5.4 years.	The study tested and quantified the relationship between swing speed and the moment of inertia of sports implements under constrained movement. Eight visually identical clubs with different moments of inertia were used. Motion capture recorded participants' maximum swings.	Swing speed decreased as moment of inertia increased, following a power relationship. The rate of decrease varied between participants and was more consistent at the upper end of the tested moment-of-inertia range.
Seo et al. (2025)	806 recreational golf practitioners in South Korea, half men and half women, with at least three months of attendance at golf academies.	Validated questionnaires were applied to assess beliefs about athletic ability, CNAAQ-2, task and ego orientation, Achievement Goal Orientation Scale, and exercise adherence, Exercise Adherence Scale. Data were analyzed using structural equation modeling with	Learning beliefs increased task orientation, which was associated with greater exercise adherence. Innate-talent beliefs increased ego orientation, also related to greater adherence. The influence of beliefs on regular golf practice occurred through motivational

Table 2.4. Continued

Study author	Sample	Procedure	Results
		a multiple mediation model to estimate relationships between beliefs, motivational orientations, and adherence.	orientations. It was concluded that both task orientation and ego orientation contribute positively to continued participation in recreational golf, although with distinct motivations.
Sim et al. (2017)	15 professional golfers and 15 amateurs.	Analysis of coordination between the thorax and pelvis during the golf swing, using vector coding to quantify coordination changes in the coupling angle between the two segments. Measurements included flexion/extension, lateral bending, and rotation movements during the backswing and downswing.	No significant difference was found in coordination patterns for rotational movement during the backswing. During the downswing, significant differences were found between professionals and amateurs in all movements: flexion/extension, professional $\gamma = 187.8^\circ$, amateur = 167.4°; lateral bending, professional $\gamma = 288.4^\circ$, amateur = 245.7°; and rotation, professional $\gamma = 232.0^\circ$, amateur = 229.5°.
Shaw, J et al. (2024)	18 talented male players, Category 1, handicap up to 5, aged 14-17 years. They were divided into experimental and control groups, matched by maturity and playing level. All were post-peak height velocity and had no strength training in the previous seven months.	Controlled 12-week experimental study. The experimental group completed two weekly progressive strength training sessions during the off-season while maintaining usual golf practice. The program included three four-week phases focused on motor competence, strength, and power. Exercises included squats, trap-bar deadlifts, isometric pulls, medicine ball throws, and horizontal and lateral jumps. Assessments included strength, power, stability, and swing performance tests, with 6-iron and driver.	The experimental group showed significant improvements in strength, power, and swing performance. Isometric strength, jump height and power, horizontal distance, Golf Movement Screen score, clubhead speed, and flight distance with both clubs increased. The control group showed no relevant changes. Supervised strength training improved motor competence and neuromuscular transfer to technical performance in young players.

Table 2.4. Continued

Study author	Sample	Procedure	Results
Sorbie et al. (2016)	15 right-handed male golfers, amateurs and professionals.	Analysis of muscle activity of the extensor carpi radialis brevis, ECRB, and flexor digitorum superficialis, FDS, in the forearms during the swing with a 7-iron and three different grip sizes. Five swings were performed by each player with each grip size.	No significant differences were found in forearm muscle activity when using the three grip sizes, $p > 0.05$. Clubhead speed increased significantly when using the undersized grip, $p = 0.044$. Amateurs showed greater forearm muscle activity during the backswing and downswing phases with all grip sizes. Grip size does not affect muscle activity, but using undersized grips increases clubhead speed.
Sorbie et al. (2018)	15 golfers, handicap = 3.3 ± 1.7 .	Movement and performance variables were collected before and after golf practice, using a motion capture system and a launch monitor.	Significant increases in X-factor and X-factor stretch were observed after practice. X-factor increased from $52.82 \pm 5.64^\circ$ to $54.06 \pm 5.61^\circ$, and X-factor stretch from $1.54 \pm 1.05^\circ$ to $1.90 \pm 1.41^\circ$. Significant differences were also found in clubhead speed, ball speed, and flight distance after practice. Performing 100 shots increased X-factor, X-factor stretch, and performance variables, improving long-game performance.
Sorbie et al. (2021)	13 golfers, mean age: 30 years; handicap: 6.1.	Clubhead velocity, CHV, and ball speed were measured. Trunk power was assessed using ballistic bench press exercises and the Wingate test.	Strong correlations were observed between ballistic bench press power and CHV, as well as between CHV and ball speed, especially with the driver and 7-iron. Power generated in the ballistic bench press was more beneficial for higher-speed swings.

Table 2.4. Continued

Study author	Sample	Procedure	Results
Turner et al. (2020)	11 experienced male golfers.	Test with 20 shots using three clubs with different moments of inertia, measured with a launch monitor.	Increasing club moment of inertia reliably reduced club and ball speed. The influence was significant and considered large.
Valença et al. (2022)	29 adolescent golfers, mean 7.8 years of experience.	Participants were divided into two groups: differential learning, DL, n = 15, and guided repetition, RB, n = 14. Both groups were subdivided by handicap, low and high. A total of 270 shots were performed across 10 sessions at 20 m, 35 m, and 50 m. Performance measurements were taken using TrackMan 4, with pre- and post-testing.	The DL group showed significant adaptations in attack, face, and dynamic loft angles, especially at distances of 35 m and 50 m. There were also improvements in score, club speed, and distance traveled for 50 m compared with the RB group. Low-handicap players in the DL group adapted more in angle variables, whereas high-handicap players improved their score at all distances. The RB group showed improvements in score and club speed at distances of 20 m and 35 m.
Wells et al. (2018)	27 Level 1 golfers.	Analysis of vertical force on force platforms during vertical jumps, CMJ, SJ, DJ, and in the isometric mid-thigh pull, IMTP. Clubhead velocity, CHV, was measured with the TrackMan system.	Significant relationships were found between clubhead speed and positive impulse during vertical jumps, CMJ, SJ, and DJ. Relationships were also found with peak force and rate of force development in the IMTP, RFD from 0-150 ms and RFD from 0-200 ms. Strong relationships were found between vertical force variables and clubhead speed.
Wells et al. (2022)	50 highly experienced golfers.	Participants performed countermovement jumps, CMJ, on Kistler force platforms in the laboratory. Variables such as positive impulse, maximum force, and jump height were measured. Clubhead velocity, CHV, was	Strong positive relationships were found between CHV and CMJ variables, such as positive impulse, net impulse, mean power, maximum power, and maximum

Table 2.4. Continued

Study author	Sample	Procedure	Results
		recorded with a TrackMan 3e monitor. Pearson correlation was used to examine the relationship between CMJ variables and CHV.	force. No significant relationship was found between CHV and jump height.

2.4. Conclusion

This study synthesized the most recent scientific evidence on the factors that influence golf performance, structured around four interdependent analytical pillars: (i) the intersegmental organization of the swing, (ii) motor control, stability, and weight distribution, (iii) performance parameters, and (iv) training adaptations and strategies. This integrated approach made it possible to understand in depth how body coordination, postural control, mechanical variables, and training strategies interact to optimize technical execution and the player's overall performance.

In the first pillar, concerning the intersegmental organization of the swing, it became evident that the effectiveness of the movement depends on the proximal-distal sequence and on the multisegmental coordination responsible for the progressive transfer of energy along the kinetic chain. The synchronized rotation of the pelvis and trunk, pelvis-thorax coupling, X-factor, and consistency of the swing plane emerge as determinants of speed and accuracy generation, distinguishing experienced players from less skilled practitioners. The literature shows that mechanical effectiveness does not result solely from joint range of motion, but above all from temporal sequencing and intersegmental fluidity, factors that ensure optimal energy transmission to the clubhead.

The second pillar, centered on motor control, stability, and weight distribution, highlighted the relevance of a stable base of support and precise regulation between the center of mass and the center of pressure in maintaining dynamic balance during the swing. More proficient players show more predictable weight-transfer patterns, lower postural variability, and greater consistency in the application of ground reaction forces. Coordination between the lower limbs and the trunk, combined with core stability, is a fundamental element both for power production and for mitigating injury risk. In addition, variations in external conditions, such as terrain slopes or club characteristics, require specific postural adaptations and motor strategies that influence technical execution.

In the third pillar, dedicated to performance parameters, it was found that shot effectiveness depends on the interaction between multiple kinematic and dynamic variables, namely clubhead speed, angle of attack, ball trajectory, and clubface orientation at impact. The accuracy and consistency of these variables are strongly associated with the player's level of technical

proficiency and neuromuscular control. In addition, instrumental parameters, such as shaft stiffness, grip type, and force balance between the biceps and triceps muscles, have been shown to significantly influence impact stability and efficiency, confirming the interdependence between technical, physical, and equipment-related factors.

Finally, the pillar concerning training adaptations and strategies showed that specific strength and power development programs, combined with stability and postural-control training, produce consistent gains in clubhead speed and distance achieved. Strategies based on differential learning and training under variable conditions proved effective in improving swing accuracy and consistency. The integration of three-dimensional motion analysis technologies, inertial sensors, IMUs, and computational modeling enables precise monitoring of the technical movement, allowing individualized adjustments and performance optimization. Similarly, careful equipment selection, including club moment of inertia and grip type, may help reduce joint overload and increase mechanical efficiency.

Thus, golf performance results from a complex interaction between intersegmental coordination, postural control, mechanical parameters, and adaptive strategies. Efficient swing execution does not depend solely on isolated strength or technique, but on the harmonious integration of kinematic, dynamic, neuromuscular, and contextual factors. Continued progress in scientific research and advances in technologies applied to golf will make it possible to deepen knowledge of the critical determinants of performance and to develop increasingly precise interventions to optimize performance, reduce injury risk, and promote an evidence-based approach to technical and physical training.

2.5. Limitations and Future Perspectives

Despite the large number of studies analyzed in this review, their limitations should be taken into consideration. First, most studies focus on professional or high-level golfers, which may limit the applicability of the findings to amateur and beginner players. In addition, there is considerable variability in the methods used to measure biomechanical and physiological variables, including different motion capture systems, force sensors, and analysis algorithms. This methodological diversity may hinder direct comparison between studies and the generalization of results.

Another relevant limitation is the lack of longitudinal studies assessing the evolution of motor adaptations over time. Most studies analyze performance in isolated training or competition sessions, without monitoring biomechanical and physiological changes over prolonged periods. This makes it difficult to understand how different training strategies influence swing development and long-term performance consistency.

To overcome these limitations, future studies should adopt more integrated and multidisciplinary approaches. Longitudinal studies are essential to better understand motor adaptations over time and to evaluate the effectiveness of different training strategies in improving performance. In addition, studies including players of different skill levels, ages, and anthropometric characteristics may provide a broader understanding of the factors that influence performance.

Technological advances may play a fundamental role in optimizing training and performance analysis in golf. Inertial sensors, artificial intelligence, and augmented reality have the potential to provide real-time feedback and personalize training interventions. Furthermore, the integration of machine learning techniques may allow a more detailed analysis of biomechanical variables and the identification of individual movement patterns that contribute to successful swing performance.

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Chapter 3. Empirical Study

Kinematic differences in golf swings between driver and iron 7 in under-18 elite golfers

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Abstract

This study deepens the understanding of biomechanical differences in swing kinematics among under-18 elite golfers when using Driver and Iron 7 clubs. Seventeen youth golfers from the Portuguese Golf Federation participated in synchronized markerless and marker-based motion capture analyses under laboratory conditions. Anthropometric characteristics, posture, swing phases, and X-Factor were assessed according to contemporary paradigms of rotational dissociation and energy transfer.

The results confirm that equipment characteristics, especially shaft length and balance point, significantly influence postural configuration and movement dynamics. Longer clubs led to greater stance width and depth, higher linear and angular velocities, and superior trunk-pelvis separation angles during backswing, consistent with previous adult studies. However, the absence of correlation between X-Factor magnitude and velocity indicates that the kinematic determinants of swing performance in adolescents differ from adult

For coaches, this reinforces that focus should be on timing and segmental sequencing rather than maximal rotational amplitude. Adjusting equipment and feedback according to developmental stage is recommended. In summary, these findings strengthen the foundation for age-appropriate training methods and technological innovation in youth golf.

Keywords:

Biomechanics, Youth sport, Golf swing, Markerless motion capture, Kinematics, X-Factor, Club length

3.1 Introduction

The biomechanical analysis of the golf swing in youth athletes is critical to optimize skill development and tailor coaching interventions appropriately. Motor control and coordination evolve significantly during adolescence, influenced by neuromuscular maturation and training experience, which in turn affect technique and performance outcomes (Horan, Evans, & Kavanagh, 2016; Smith, Murray, & Olivier, 2015). Understanding these developmental biomechanical underpinnings is essential for designing age-specific training protocols that balance skill acquisition with injury prevention.

Equipment characteristics, especially club shaft length, play a pivotal role in shaping stance and swing mechanics in adolescent golfers (Brown et al., 2021). The longer shaft of the Driver demands increased stance width and depth to accommodate the greater moment of inertia and arc radius, with consequential effects on trunk rotation and segmental sequencing (Nesbit, 2013). These postural and kinematic adjustments have been associated with higher clubhead velocities during the backswing, downswing, and ball impact phases relative to shorter irons such as the Iron 7 (Joyce, Burnett, & Ball, 2020).

However, youth golfers exhibit unique biomechanical patterns compared to adults, including differences in the magnitude and timing of the X-Factor, as well as in coordination strategies employed during the swing (Cheetham et al., 2001; Kwon et al., 2012). Unlike mature athletes, adolescents may rely less on maximal trunk-pelvis dissociation and more on coordinated segmental efforts to generate swing speed, reflecting ongoing neuromuscular development and motor learning stages (Figueiredo, Mesa, & Vilas-Boas, 2020). This is supported by the lack of significant correlation between X-Factor and swing speed observed in some youth studies, suggesting alternative biomechanical determinants of performance (Brown et al., 2021). Comparisons with biomechanical studies in other adolescent sports, such as tennis and baseball, reveal common developmental trajectories in segmental coordination and rotational mechanics, underscoring the broader relevance of maturation-informed coaching models (Sannicandro, Cofano, & Rosa, 2022). These cross-disciplinary insights support a holistic approach to youth athletic development that prioritizes the preservation of temporal consistency in movement patterns while adapting to equipment demands.

The integration of dual motion capture methodologies—combining marker-based precision with the ecological validity of markerless systems—enhances the reliability and applicability of biomechanical data in youth sports research (Preatoni, Cavallari, & Faina, 2021; Taylor, Hobbs, & Toward, 2022). This technological synergy facilitates longitudinal tracking of biomechanical adaptations and allows for more nuanced analyses of how varying club characteristics affect swing kinematics in real-world training conditions.

This study builds on the growing body of evidence highlighting the interplay between equipment geometry, motor development, and biomechanical strategy in youth golf. By directly comparing swing mechanics using two clubs of distinct shaft lengths, the Driver and Iron 7, the research aims to elucidate key factors that inform effective coaching, equipment selection, and skill progression in adolescent golfers.

3.2. Methods

3.2.1. Participants

A sample of 17 male under-18 golf players from the Portuguese Golf Federation, aged between 14 and 18 years, were invited to participate in this study. The participants had 15.9 ± 1.2 years of age, 1.73 ± 0.08 m of height, 62.6 ± 6.9 kg of mass, and a body mass index of 20.9 ± 1.5 m/kg². Participant selection was based on national federation rankings and verified training history, ensuring a representative sample of the country's youth elite. Participants and legal guardians signed a written informed consent form in accordance with the Helsinki declaration.

3.2.2. Experimental setup

Swings were performed indoors on a 15 x 1.5 m synthetic turf system, with tee location standardized and safety netting positioned 5 meters away to intercept balls post-impact.

Three-dimensional kinematic data of the participant was recorded with a Markerless motion capture system comprising 8 Miquis cameras (Qualisys AB, Sweden) operating at 100 Hz and 720p resolution. Additionally, and in synchrony, a marker-based motion capture system

composed by 12 Oqus cameras (Qualisys AB, Sweden), operating at 200 Hz, was used to record the movement of the club. For that purpose, 12 mm retroreflective markers were placed on the club's distal portion of the top line, at the posterior aspect of the shaft, at the transition between the shaft and grip, and on both sides of the midpoint of the shaft. A 1 cm² retroreflective square tape was placed on top of the golf ball to identify its initial position. Participants completed five maximal-effort swings each with Driver and Iron 7, using their own clubs to minimize equipment unfamiliarity. At least 60 seconds of interval were observed between trials.

The protocol received ethical approval from the local institution Ethics Committee, with the approval number CEFAD 33/2025.

3.2.3. Data Analysis

The participant's movements were identified with the Markerless motion tracking software Theia Markerless v.2022.1.2309.20 (Theia Markerless, Canada), resulting in a 6 degrees-of-freedom representation. The club markers were identified in the Qualisys Track Manager v2022.2.7700 (Qualisys AB, Sweden), and gaps in their trajectories interpolated in the same software using a polynomial interpolation. Both the marker-based and Markerless data were imported in Visual3D v2021.11.3 (HAS-Motion, Canada), where data fusion and analysis was performed.

The swing was analysed during the phases of: (i) backswing, when the club head exceeds 0.1 m/s and is moved upwards and backwards; and (ii) downswing, when the player accelerates the club downwards and forward until striking the ball.

The initial stance was considered as the position at the take-away, and the distance between feet (stance width), and the distance between the club head and the midpoint between ankles (stance depth) were retrieved. The swing total duration and the relative proportion of the backswing and downswing were calculated.

The club head velocity was calculated as the magnitude of its linear velocity, and its maximum velocity during the backswing and downswing were calculated. The velocity at the instant of contact with the ball was also retrieved. The X-Factor at the end of the backswing, and at ball contact was calculated as the angle between the shoulders line and the pelvis.

All variables were calculated for each of the five trials, and the average value was considered for further analysis and comparisons. A visual representation of the experimental setup and variables can be observed in Figure 3.1.

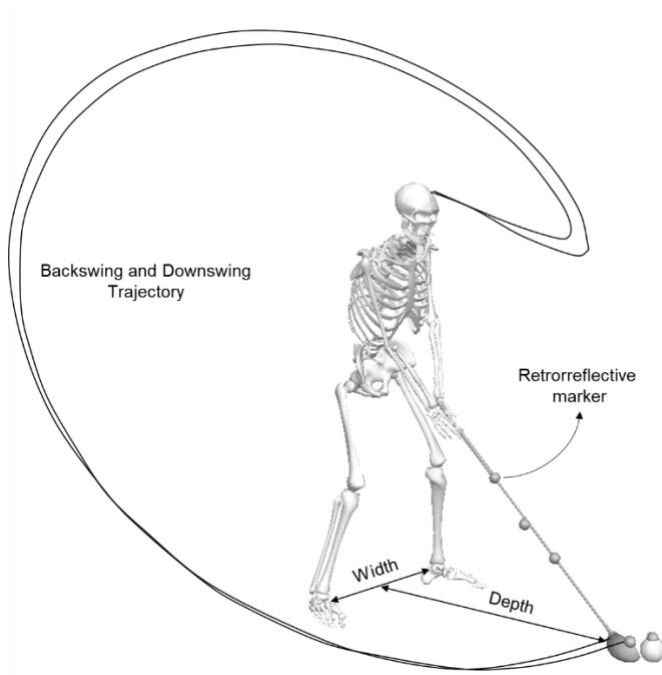


Figure 3.1. Representation of the experimental setup and retroreflective marker placement on the club. The backswing and downswing club trajectory are highlighted, and the stance width and depth defined.

3.2.4. Statistical Analysis

Statistical analyses were performed in IBM SPSS Statistics 29 (IBM, USA). Normality of data distribution was assessed with the Kolmogorov-Smirnov test, after which a repeated measures MANOVA teste was performed for multivariate analysis. The correlation between X-Factor at the end of Backswing and the club speed during Downswing and Ball contact was assessed by Pearson correlation in Matlab R2025a (The MathWorks, USA). All statistical tests considered an $\alpha = 0.05$.

3.3. Results

A repeated-measures MANOVA showed a multivariate effect using Pillai's trace, indicating an effect of club used, $V = 0.993$, $F(9, 8) = 127.545$, $p < .001$, $\eta_p^2 = 0.993$.

As reported in Table 3.1., follow-up univariate tests showed that a swing with the Driver features a larger stance depth ($F(1,16) = 130.3$, $p < 0.001$, $\eta_p^2 = 0.891$) and width ($F(1,16) = 273.4$, $p < 0.001$, $\eta_p^2 = 0.945$). Although no differences were found in the swing total duration and its phases relative durations, both the maximum swing velocity during the backswing ($F(1,16) = 150.6$, $p < 0.001$, $\eta_p^2 = 0.904$), downswing ($F(1,16) = 600.0$, $p < 0.001$, $\eta_p^2 = 0.974$) and ball contact ($F(1,16) = 563.9$, $p < 0.001$, $\eta_p^2 = 0.972$) are greater when performed with the Driver. The X-Factor is also greater when using the Driver at the end of the backswing phase ($F(1,16) = 205.1$, $p < 0.001$, $\eta_p^2 = 0.411$), but not at ball contact.

Table 3.1. Statistical results of the comparison between a swing performed with a driver or an Iron 7 club.

CATEGORY	VARIABLE	DRIVER	IRON 7	<i>p</i> -value	<i>ES</i>
Initial Stance	Stance Depth (% Height)	63.9 ± 2.7	45.2 ± 2.7	<0.001	0.891
	Stance Width (% Shoulder Width)	195.5 ± 19.57	152.6 ± 19.1	<0.001	0.945
Swing Duration	Total duration (ms)	1197.9 ± 230.2	1211.0 ± 179.6	0.558	0.022
	Backswing (%Total)	78.3 ± 3.1	78.8 ± 3.0	0.249	0.082
	Downswing (%Total)	21.7 ± 3.1	21.2 ± 3.0	0.249	0.082
Maximum Swing Velocity	Backswing (km/h)	44.3 ± 8.8	33.1 ± 5.8	<0.001	0.904
	Downswing (km/h)	136.6 ± 6.7	110.9 ± 5.3	<0.001	0.974

	Ball Contact (km/h)	131.3 ± 6.0	107.7 ± 5.5	<0.001	0.972
X-Factor	Backswing Top	36.9 ± 9.6	32.01 ± 6.4	0.004	0.411
	Ball Contact	6.4 ± 3.9	6.0 ± 3.7	0.465	0.028

No significant correlation was found between the X-Factor at the end of the backswing phase and downswing maximum club speed, either with the Driver ($r=-0.068$, $p=0.795$) or the Iron7 ($r=-0.086$, $p=0.742$) clubs. Similarly, no correlation was found with the X-Factor and the club speed at ball impact with the Driver ($r=-0.111$, $p=0.670$) and Iron 7 ($r=-0.149$, $p=0.568$) clubs.

3.4. Discussion

The present study offers valuable insights into the biomechanical adaptations induced by equipment variation in junior golfers, specifically when comparing swing kinematics with the driver and 7-iron. Our results indicate that the increased club length and mass substantially alter posture and peak angular velocities, consistent with previous research conducted in both laboratory-controlled and applied performance environments (Brown et al., 2021; Nesbit, 2013). This reinforces the premise that equipment geometry—particularly shaft length—influences not only technical preparation, as seen in postural adaptations, but also dynamic kinematic properties, including peak velocities and rotational dissociation. These findings extend adult-centered studies to the youth context, highlighting the plasticity of motor strategies during skill acquisition and underscoring the need for age-appropriate training guidelines and equipment recommendations (Ericsson et al., 1993; Figueiredo et al., 2020).

The higher peak velocities observed with the driver confirm established patterns in adult populations. This study also corroborates previous literature supporting the link between speed and distance, positioning shaft length as the main determinant (Nesbit, 2013). Interestingly, our results demonstrate that junior athletes achieve such outcomes without altering total swing time or phase proportion (Joyce, Burnett & Ball, 2020), as swing duration and intermediate phase lengths remained statistically invariant across clubs.

Conversely, swing duration and intra-swing timing ratios (percentage of total duration) remained statistically invariant between clubs, pointing to preservation of temporal patterns through motor control, despite changes in equipment. Assuming equal angular range of motion, the absence of differences in total swing duration and timing indicate that swings with the Driver and Iron7 club have an identical angular velocity. As the club velocity at its tip is the product between angular velocity and distance to the axis of rotation, the results indicate that the final determinant of speed is indeed the club shaft length. Naturally, other effects may promote additional energy transfer, such as shaft flex (as energy storage) and the pendulum effect of the shoulder and elbow (momentum transfer)

This temporal invariance highlights the robustness of internal motor programs during adolescent maturation (Horan, Evans & Kavanagh, 2016) and emphasizes that temporal patterns are preserved through motor control, regardless of equipment changes. With identical angular ranges of motion, swing timing and speed appear governed by club geometry—the clubhead's linear velocity being a product of angular speed and distance to the rotation axis.

A key contribution of this study is the differentiation of X-Factor dynamics. Although the maximum rotational dissociation between pelvis and shoulders was higher with the driver (36.9° vs. 32.0° with the 7-iron), its lack of significant correlation with clubhead speed among juniors indicates that segmental sequencing and coordination exert stronger influence on kinetic outcomes than angular amplitude alone (Cheetham et al., 2001; Kwon et al., 2012; Brown et al., 2021). This contrasts with adult findings and may suggest the distinct roles of maturation and coordination in young athletes. Notably, no significant difference appeared at ball impact, aligning with the “uncoiling” hypothesis during the downswing phase. These results reinforce that, for junior athletes, swing speed depends more on segmental force production and interjoint coordination than on pelvis–shoulder separation, suggesting that training focusing on rhythm, timing, and neuromuscular development is preferable to that emphasizing biomechanical extremes, especially in youth populations (Ericsson, Krampe & Tesch-Römer, 1993; Smith, Murray & Olivier, 2015).

From a methodological standpoint, this study advances the field by supporting the reliability, validity, and practical utility of markerless motion capture in golf swing analysis. The use of markerless motion capture techniques provides greater ecological validity and practicality for future field-based biomechanics research, supporting ongoing technological integration in golf

science (Taylor et al., 2022). However, this technology is still limited to the analysis of human movement, and therefore the use of conventional retroreflective markers is still needed to enable a club-based analysis.

The implications of these findings extend across disciplines; skill acquisition focused on sequencing aligns with recommended practices not only in golf but also in tennis, baseball, and other rotational sports (Sannicandro, Cofano & Rosa, 2022; Elliott, Reid & Crespo, 2009). The importance of load management and progressive adaptation in youth golf training, highlighted by McCarroll & Gioe (1982) and current positions, is reaffirmed by our demonstration of efficient performance achieved without biomechanical extremes.

The study's limitations include sample size and group homogeneity. Future research should encompass more diverse cohorts and examine long-term effects of individualized interventions. Integrating segmental coordination and swing rhythm as pedagogical priorities may better accommodate constraints related to physical maturation, motor coordination, or individual style among adolescent athletes.

In conclusion, our findings confirm that in junior golfers, swing modifications induced by equipment are accommodated through postural and coordination adaptations rather than fundamental changes in rhythm or segmental timing. This evidence supports individualized and context-sensitive training models grounded in the latest biomechanical and motor learning research, promoting optimal technical development, enjoyment, and athlete retention in golf and similar sports.

3.5. Conclusions

The present study elucidates the considerable biomechanical adaptations enacted by Portuguese youth elite golfers when performing with the Driver and Iron 7. Quantitative analyses revealed that the use of the Driver elicited a significant increase in stance width and stance depth, underscoring the influence of equipment geometry on initial swing set-up. Furthermore, the Driver prompted considerably higher maximal swing velocities across critical swing phases, including the backswing, the downswing, and at impact, all significantly surpassing those achieved with the Iron 7.

Additionally, the X-Factor at the end of the backswing was markedly greater when using the Driver compared with the Iron 7, reflecting a mechanical adaptation to the extended lever arm and increased inertia imposed by the longer club. Despite these inter-club kinematic discrepancies, temporal metrics such as total swing duration and swing phase ratios remained invariant, indicating the maintenance of temporal motor control despite biomechanical perturbation.

Crucially, no significant correlation between X-Factor magnitude and swing speed for either club, challenging paradigms established in adult populations and suggesting that, during adolescence, effective sequencing and segmental motor coordination may outweigh the contribution of peak trunk-pelvis dissociation to velocity generation.

3.6. Conflict Of Interests

The author Nélson Ribeiro was, at the time of data collection, a paid employee of the Portuguese Golf Federation. The remaining authors do not have conflicting interests.

3.7. Funding

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Chapter 4. General Discussion

This thesis aimed to analyze the biomechanical determinants of the golf swing by integrating the evidence available in the literature with an empirical assessment of kinematic differences between the Driver and the 7-iron in elite under-18 golfers. The systematic review showed that golf swing performance is not determined by a single mechanical variable, but by the interaction between intersegmental coordination, pelvis-trunk coupling, ground interaction, neuromuscular control, club trajectory, and technical consistency. Across the literature, efficient performance has consistently been associated with a well-organized proximal-to-distal sequence, effective weight transfer, stable interaction with the ground, and the capacity to generate high clubhead speed without compromising control or repeatability (Chu et al., 2010; Han et al., 2019; Hume et al., 2005; Milburn, 1982).

The systematic review also highlighted that the X-Factor has received considerable attention as a potential determinant of swing power. Pelvis-trunk separation has often been interpreted as a mechanism for storing elastic energy during the backswing and enhancing rotational acceleration during the downswing (Cheetham et al., 2001; Hume et al., 2005). However, the evidence is not entirely consistent. Several studies have shown that X-Factor values depend strongly on the computational method used, the anatomical model adopted, and the phase of the swing analyzed (Brown et al., 2013; Joyce et al., 2010; Y.-H. Kwon et al., 2013). Therefore, although pelvis-trunk dissociation is biomechanically relevant, the literature suggests that the quality of segmental sequencing, timing, and coordination may be more decisive than the absolute magnitude of rotation alone.

The empirical study extended these findings to elite youth golfers by directly comparing swing kinematics with the Driver and the 7-iron. The results showed that equipment characteristics significantly influenced the initial setup and movement dynamics. The Driver produced greater stance width and stance depth, higher maximum swing velocities during the backswing, downswing, and ball contact phases, and a greater X-Factor at the top of the backswing when compared with the 7-iron. In contrast, total swing duration and the relative duration of swing phases did not differ significantly between clubs, suggesting that these young golfers preserved a stable temporal structure despite changing equipment demands.

A particularly important finding was the absence of significant correlations between X-Factor magnitude and swing speed in both clubs. Although the Driver produced a higher X-Factor at

the top of the backswing, this larger rotational separation did not translate directly into higher club velocity. This result challenges a simplistic interpretation of the X-Factor as a direct predictor of performance, especially in adolescent athletes. Instead, it supports the view that, in youth golfers, swing speed may depend more on coordination, sequencing, rhythm, and efficient energy transfer than on maximizing pelvis-trunk separation.

The findings of the empirical study are broadly consistent with the main patterns identified in the systematic review, particularly regarding the multifactorial nature of golf swing performance. The review showed that skilled golfers typically exhibit better intersegmental coordination, more efficient transfer of energy along the kinetic chain, and more consistent control of the clubhead trajectory (Kwon et al., 2021; Morrison et al., 2016; Tinmark et al., 2010). The empirical results support this framework by showing that elite youth golfers were able to adapt to two clubs with distinct mechanical demands without substantially altering the temporal organization of the swing.

The Driver generated higher velocities than the 7-iron during the backswing, downswing, and ball contact phases. This agrees with previous biomechanical evidence showing that longer clubs tend to produce greater clubhead speeds due to their larger swing radius and longer lever arm (Egret et al., 2003; Joyce, 2017a, 2017b). The empirical finding that total swing duration remained stable between clubs is particularly relevant, as it suggests that the higher linear velocity of the Driver may be explained largely by club geometry rather than by a faster global swing rhythm. From a mechanical perspective, when angular timing is preserved, the longer radius of the Driver allows the clubhead to travel at a higher linear velocity, even if the underlying temporal structure of the movement remains similar.

The review also emphasized that efficient golf swings are based on the coordinated contribution of the lower limbs, pelvis, trunk, upper limbs, wrists, and club (Han et al., 2019; Milburn, 1982; Nesbit & Serrano, 2005). The empirical study reinforces this principle by showing that young elite golfers did not simply swing the Driver faster in a generalized way. Instead, they modified posture and rotational configuration while preserving timing. This indicates that their motor system accommodated equipment constraints through specific kinematic adjustments rather than through a complete reorganization of the swing.

The empirical results also refine the interpretation of the X-Factor. In adult golfers, larger pelvis-trunk separation has often been associated with greater power production, particularly when accompanied by effective sequencing and trunk-pelvis coupling (Cheetham et al., 2001; McHugh et al., 2024; Myers et al., 2008). However, the absence of a significant correlation between X-Factor and swing speed in this study suggests that this relationship may be different in adolescent golfers. This is consistent with studies showing that maturation, neuromuscular control, and coordination strategies influence swing mechanics in younger athletes (Brožka et al., 2023; Gryc et al., 2023). Therefore, the empirical findings do not contradict the literature, but rather specify its application to youth golfers.

One of the central contributions of this thesis is the distinction between rotational amplitude and coordination quality. The systematic review showed that pelvis-trunk separation is relevant, but it also demonstrated that the X-Factor should not be interpreted in isolation. Studies by Brown et al. (2013), Joyce et al. (2010), and Kwon et al. (2013) showed that X-Factor values vary according to the calculation method, while other studies emphasized that timing, sequencing, and segmental acceleration patterns are essential for translating rotation into clubhead speed (Madrid et al., 2020; McHugh et al., 2024; Tinmark et al., 2010).

The empirical study contributes to this discussion by showing that the Driver produced a significantly higher X-Factor at the top of the backswing than the 7-iron, but this difference was not associated with higher swing speed at the individual level. This suggests that, in elite youth golfers, the capacity to separate the pelvis and trunk may reflect an adaptation to club length and swing arc rather than a direct determinant of velocity. The longer Driver may naturally encourage a wider setup and greater rotational displacement, but this does not necessarily mean that athletes who rotate more are the ones who generate more speed.

This finding is particularly important for youth golf coaching. In adolescent athletes, neuromuscular development is still ongoing, and coordination strategies may be less stable than in mature adult players. Brožka et al. (2023) showed that changes in physical development, including height, lean mass, jump power, and lower-limb strength, are associated with changes in clubhead speed in junior golfers. Gryc et al. (2023) also reported sex-related differences in pelvic and thoracic rotation among junior golfers, suggesting that maturation and biological development influence rotational mechanics. In this context, maximizing X-Factor amplitude

may be less important than developing efficient sequencing, stable rhythm, and appropriate force transfer.

The results therefore support a more nuanced interpretation of the X-Factor. Rather than being treated as a universal performance target, it should be considered one component of a broader coordination system. A golfer may achieve a high X-Factor but fail to convert it into clubhead speed if the downswing sequence is poorly timed, if trunk deceleration is ineffective, or if distal segments are released too early. Conversely, a golfer with a moderate X-Factor may generate high speed if the pelvis, trunk, arms, wrists, and club are sequenced efficiently. This interpretation is consistent with the view that expert performance depends not only on movement amplitude, but also on the ability to organize degrees of freedom into functional coordination patterns (Morrison et al., 2016).

The comparison between the Driver and the 7-iron clearly showed that equipment characteristics influence swing organization. The Driver, because of its longer shaft and greater swing radius, led to a wider and deeper stance. This setup adaptation is biomechanically coherent, as a longer club requires the golfer to position the body farther from the ball and to create a larger functional base of support. A wider stance may help stabilize the body against greater rotational and inertial demands, particularly during the transition and downswing phases.

The Driver also produced higher maximum velocities during the backswing, downswing, and ball contact phases. This is consistent with the mechanical effect of a longer lever arm. If the golfer preserves a similar angular rhythm between clubs, the clubhead of the Driver will cover a greater linear distance and therefore reach a higher linear velocity. This supports previous evidence showing that club type influences kinematic variables and movement organization (Egret et al., 2003; Joyce, 2017a, 2017b; Liu et al., 2025). However, the empirical study adds an important developmental perspective by showing that elite under-18 golfers can adjust to these mechanical differences while maintaining stable temporal proportions.

The absence of significant differences in total swing duration and phase ratios suggests that the athletes preserved a consistent internal timing structure across clubs. This is relevant because timing stability is a key feature of skilled motor behavior. In practical terms, the young golfers did not appear to create speed with the Driver by rushing the downswing or changing the overall

rhythm of the movement. Instead, they maintained a stable temporal pattern while adapting posture, swing arc, and rotational configuration. This suggests a relatively advanced level of motor control for their age group.

The increased X-Factor observed with the Driver can also be interpreted as a response to equipment geometry. The longer club may require a larger backswing arc and greater trunk-pelvis dissociation to position the club effectively at the top of the backswing. However, because this greater X-Factor was not correlated with swing speed, it should be understood as an adaptation to the task rather than as an isolated performance determinant. The club changes the constraints of the movement, but the athlete's ability to organize those constraints efficiently depends on coordination, physical capacity, and technical maturity.

The results of this thesis have direct implications for the training of young golfers. Coaches should avoid using adult biomechanical models in a rigid or direct way with adolescent athletes. Although concepts such as X-Factor, ground reaction forces, and proximal-to-distal sequencing are important, young golfers are still developing physically, coordinatively, and neurologically. Training should therefore prioritize the quality of movement organization rather than the pursuit of extreme rotational positions.

The lack of association between X-Factor magnitude and swing speed suggests that coaches should not overemphasize maximal pelvis-trunk separation in youth golfers. Encouraging excessive rotation may increase mechanical stress without necessarily improving performance. Instead, training should focus on rhythm, transition control, sequencing, and the ability to transfer energy smoothly from the lower body to the club. This is particularly important because the review showed that efficient golfers are distinguished not only by the amount of rotation they produce, but by how they coordinate that rotation across the swing phases (Han et al., 2019; Morrison et al., 2016; Tinmark et al., 2010).

Equipment should be adapted to the athlete's developmental stage. The empirical results showed that the Driver substantially changes stance configuration, velocity, and rotational organization. Therefore, inappropriate club length, mass, shaft characteristics, or balance point may impose excessive technical and physical demands on young players. Coaches and club fitters should consider height, strength, maturity, coordination level, and swing consistency when

recommending equipment. In youth golf, equipment fitting should not aim only to maximize distance, but also to support stable motor learning and safe technical development.

Training programs should integrate physical development with technical instruction. The literature shows that lower-limb power, trunk strength, hip mobility, and core stability are related to swing performance (Brožka et al., 2023; Johansen et al., 2023; Sell et al., 2007). However, these capacities should be developed in a way that supports coordination rather than replacing it. Strength and power training should therefore be combined with exercises that promote balance, postural control, dissociation, rhythm, and controlled acceleration.

The findings support an individualized coaching model. Two young golfers may produce similar clubhead speeds through different coordination strategies. One may rely more on rotational speed, another on timing and distal release, and another on stable ground interaction. The coach's role is not to force all athletes into the same model, but to identify each player's functional pattern and guide it toward greater efficiency, repeatability, and safety.

From a methodological perspective, this thesis contributes to the growing use of motion capture technologies in applied sport biomechanics. The empirical study combined markerless motion capture for body movement analysis with marker-based capture for club motion. This dual approach is particularly relevant because it addresses two important needs in golf biomechanics: capturing human movement with greater ecological feasibility and measuring the club with sufficient precision.

Marker-based systems remain highly valuable for tracking the golf club, where small positional errors may strongly affect the interpretation of clubhead velocity, path, and impact-related variables. At the same time, markerless motion capture has practical advantages for athlete assessment, especially because it reduces preparation time, avoids marker-placement errors on the body, and may be more acceptable in applied training contexts. The combination of both systems therefore represents a useful compromise between laboratory precision and ecological applicability.

This methodological integration is especially promising in youth sport. Young athletes may benefit from repeated monitoring across the season, but traditional marker-based protocols can be time-consuming and difficult to implement frequently. Markerless systems may facilitate

longitudinal assessment of posture, swing phases, pelvis-trunk motion, and gross kinematic patterns in more realistic training settings. When combined with targeted marker-based tracking of the club, the approach can provide coaches with meaningful biomechanical information without requiring a fully invasive or overly complex laboratory protocol.

However, this approach should be interpreted with methodological caution. Markerless systems may be less accurate for fine joint rotations, rapid distal movements, and occluded segments, especially during high-speed actions such as the golf swing. Therefore, their use should be validated against reference systems and applied according to the specific variable of interest. For broad kinematic analysis and coaching feedback, markerless systems may be highly useful. For precise club mechanics, wrist motion, or impact dynamics, marker-based tracking, force platforms, radar systems, or high-speed cameras may still be necessary.

The present thesis has some limitations that should be considered when interpreting the findings. The systematic review included studies with substantial methodological heterogeneity. The literature on golf biomechanics varies widely in terms of sample characteristics, handicap level, age, sex, club type, measurement systems, swing protocols, and biomechanical models. These differences make direct comparison across studies difficult and limit the possibility of drawing universal conclusions about specific variables such as the X-Factor or segmental sequencing.

The empirical study also has limitations. The sample included 17 male under-18 elite golfers, which provides valuable insight into a specific and underexplored population, but limits generalization to female golfers, recreational youth players, adult golfers, or athletes at different stages of maturation. The inclusion of only male athletes is particularly relevant because previous research has shown sex-related differences in pelvic and thoracic rotation, movement variability, and clubhead speed (Gryc et al., 2023; Horan et al., 2011; Horan et al., 2010).

The laboratory context is another limitation. Although laboratory assessment allows standardized data collection and greater control over measurement conditions, it does not fully reproduce the perceptual, environmental, and performance constraints of real golf play. Variables such as target perception, ball flight feedback, terrain slope, competitive pressure, and course conditions may influence swing organization in ways that are not captured indoors.

The empirical study was also limited to kinematic analysis. Although kinematics provides essential information about posture, timing, velocity, and segmental motion, it does not directly measure the forces, moments, muscle activation patterns, or mechanical loads underlying the movement. The absence of kinetic data, such as ground reaction forces, limits interpretation of player-ground interaction. Similarly, the absence of electromyography prevents analysis of neuromuscular activation strategies, muscle timing, and co-contraction patterns. These dimensions are important because the systematic review showed that performance and injury prevention depend not only on movement geometry, but also on force production, muscular coordination, and load management.

Finally, the empirical design was cross-sectional. This means that the study describes differences between clubs at a specific moment in the athletes' development, but does not allow conclusions about how these kinematic patterns evolve over time. In youth sport, this is particularly important because growth, maturation, strength development, and training experience may substantially alter swing mechanics across adolescence.

Future research should adopt longitudinal designs to examine how golf swing biomechanics evolve throughout adolescence. Tracking young golfers over several seasons would allow researchers to understand how growth, maturation, strength development, and training experience influence clubhead speed, X-Factor, segmental sequencing, and equipment adaptation. Such studies would be especially valuable for distinguishing temporary maturational effects from stable technical characteristics.

Future studies should also include female youth golfers and compare sex-specific developmental trajectories. Given the evidence that male and female golfers may differ in pelvic rotation, thoracic rotation, movement variability, and clubhead speed (Gryc et al., 2023; Horan et al., 2010; Zheng et al., 2008), it is important to avoid building youth golf models based only on male samples. Including female athletes would strengthen the ecological and practical relevance of biomechanical recommendations.

Biological maturation should also be assessed more directly. Chronological age alone is insufficient to characterize adolescent athletes. Measures such as maturity offset, peak height velocity, growth rate, or maturity status could help explain differences in strength, coordination,

range of motion, and swing organization. This would allow researchers and coaches to better understand whether a given kinematic pattern reflects technical ability, maturational stage, or physical development.

Future research should integrate kinematic, kinetic, and electromyographic data. Combining motion capture with force platforms would allow a deeper understanding of how young golfers use the ground to generate rotation and transfer energy. Adding EMG would help clarify how muscle activation patterns support timing, stability, and clubhead speed. This integrated approach would be especially useful for investigating whether young golfers rely more on distal acceleration, trunk rotation, lower-limb force production, or neuromuscular coordination to generate speed.

Finally, future studies should validate laboratory findings in field conditions. The use of portable markerless systems, wearable sensors, radar-based launch monitors, and instrumented clubs may allow biomechanical assessment during actual practice sessions or on-course environments. This would help determine whether the stable timing patterns observed in the laboratory are preserved under real playing conditions. Field validation is essential for translating biomechanical evidence into practical coaching recommendations.

Overall, this thesis reinforces that the golf swing in elite youth players should be understood as a coordinated, adaptive, and developmentally sensitive movement. The Driver and the 7-iron impose different mechanical constraints, but skilled young golfers appear capable of adapting their posture and velocity while preserving temporal organization. For coaches, this supports a training philosophy centered on coordination, rhythm, individualized development, and appropriate equipment selection rather than on isolated biomechanical targets such as maximal X-Factor amplitude.

Chapter 5. General Conclusions

The general aim of this thesis was to analyze the biomechanical determinants of the golf swing by integrating the available scientific evidence and empirically assessing the kinematic differences between the Driver and the 7-iron in elite youth golfers. Taken together, the systematic review and the empirical study support the conclusion that golf swing performance is a complex and multifactorial phenomenon, shaped by the interaction between mechanical, coordinative, neuromuscular, technical, and equipment-related factors. The swing cannot be adequately explained by a single variable, such as clubhead speed, X-Factor, or rotational amplitude. Instead, performance emerges from the capacity to organize the whole body into an efficient movement sequence that allows energy to be generated, transferred, and applied to the club in a controlled and repeatable way.

The evidence synthesized in the systematic review showed that the main biomechanical determinants of the golf swing include proximal-to-distal sequencing, pelvis-trunk coordination, ground interaction, weight transfer, postural stability, neuromuscular control, clubhead trajectory, and consistency of impact. These determinants interact throughout the different phases of the swing and contribute jointly to distance, accuracy, and technical repeatability. In this sense, the golf swing should be understood as an integrated kinetic-chain movement, in which the lower limbs, pelvis, trunk, upper limbs, wrists, and club act in a coordinated manner. Efficient performance depends not only on the ability to produce force or rotation, but also on the capacity to time this production appropriately within the movement.

A fundamental conclusion of this thesis is that intersegmental coordination and motor control are fundamental to swing efficiency. The review showed that skilled golfers are generally characterized by more effective segmental sequencing, better control of pelvis-trunk interaction, more stable weight transfer, and lower movement variability. These characteristics allow mechanical energy to be transferred progressively from proximal to distal segments, contributing to higher clubhead speed while preserving control over the clubface and impact conditions. Therefore, the quality of the sequence appears to be more relevant than the isolated magnitude of individual joint or segment rotations. This conclusion is particularly important because it shifts the interpretation of golf performance away from isolated biomechanical markers and toward the coordination of the whole movement system.

The empirical study contributed to this understanding by analyzing elite under-18 golfers and comparing two clubs with different mechanical and technical demands. The results showed that the Driver and the 7-iron led to different kinematic organizations of the swing. The Driver was associated with a wider and deeper stance, higher maximum velocities during the backswing, downswing, and ball contact phases, and a greater X-Factor at the top of the backswing. These findings indicate that young elite golfers are able to adapt their setup and movement configuration according to the characteristics of the club. The longer shaft and larger swing radius of the Driver appear to require greater postural adjustment and allow higher velocity production, whereas the 7-iron is associated with a more controlled configuration, consistent with its technical function in accuracy and trajectory control.

However, despite these differences, the empirical study also showed that total swing duration and the relative duration of swing phases did not differ significantly between the Driver and the 7-iron. This finding suggests that elite youth golfers preserve a relatively stable temporal structure across clubs, even when adapting to different mechanical constraints. In practical terms, these athletes do not appear to generate higher Driver velocities by fundamentally changing the rhythm or timing of the swing. Instead, they seem to maintain a stable temporal organization while adjusting stance, rotational configuration, and velocity output. This reinforces the idea that skilled movement in youth golf is based not only on producing speed, but on preserving coordination under changing task constraints.

The findings regarding the X-Factor are particularly relevant. Although the Driver produced a greater X-Factor at the top of the backswing than the 7-iron, this variable was not significantly correlated with swing speed. This suggests that, in elite youth golfers, greater pelvis-trunk separation should not be interpreted as a direct or isolated predictor of performance. The X-Factor may represent an important component of swing organization, especially as an indicator of pelvis-trunk dissociation and rotational positioning, but its performance value depends on how it is integrated into the overall sequence of the swing. A high X-Factor without appropriate timing, trunk control, lower-limb contribution, and distal release may not result in higher clubhead speed. Conversely, a moderate X-Factor may be functionally effective when combined with efficient sequencing and stable motor control.

This conclusion has particular relevance for young athletes. In under-18 golfers, physical growth, biological maturation, strength development, flexibility, and neuromuscular coordination are still evolving. For this reason, biomechanical variables derived from adult models should not be applied rigidly to youth populations. The results of this thesis suggest that youth golfers should not be encouraged simply to maximize rotational amplitude or pelvis-trunk separation. Instead, training should emphasize coordination quality, rhythm, transition control, postural stability, and the progressive development of an efficient kinetic sequence. The X-Factor may be useful as one monitoring variable, but it should be interpreted cautiously and always in relation to the broader movement pattern.

From a practical perspective, this thesis reinforces the importance of individualized training in youth golf. Coaches should consider that young golfers may achieve similar performance outcomes through different biomechanical strategies. Some athletes may rely more on rotational velocity, others on timing, stability, or distal control of the club. Therefore, training should not be based on a single technical model imposed equally on all players. Instead, coaches should identify each athlete's functional movement pattern and guide its development toward greater efficiency, consistency, and safety. This includes developing lower-limb stability, trunk control, hip mobility, balance, rhythm, and coordinated energy transfer throughout the kinetic chain.

The results also support the integration of physical conditioning with technical training. Since swing performance depends on the interaction between movement coordination and physical capacities, strength and conditioning programs for young golfers should be designed to support technical development rather than simply increase isolated force production. Core stability, lower-limb strength, rotational power, mobility, and balance should be developed in ways that enhance swing mechanics and reduce injury risk. In youth athletes, this integration must also respect maturational status, growth-related changes, and individual variability in physical development.

Equipment selection is another important practical implication. The comparison between the Driver and the 7-iron showed that club characteristics influence stance, velocity, rotational organization, and movement demands. Therefore, equipment should be adapted to the golfer's anthropometric characteristics, strength, maturity, coordination level, and technical consistency. In young golfers, club fitting should not focus exclusively on maximizing distance. It should

also support stable motor learning, appropriate posture, controllable swing mechanics, and safe progression. A club that is too long, too heavy, or poorly matched to the athlete may increase compensatory movements, technical variability, or mechanical overload.

This thesis also highlights the applied value of biomechanical assessment in youth golf. By identifying how young golfers adapt to different clubs and how variables such as X-Factor, stance configuration, velocity, and timing interact, biomechanical analysis can provide coaches with objective information to support training decisions. Such information may help distinguish between technical limitations, physical constraints, and equipment-related adaptations. In this way, biomechanics can contribute not only to performance optimization, but also to individualized athlete development and injury prevention.

Overall, the thesis answers its specific objectives by systematizing the scientific literature on golf swing biomechanics, identifying the main kinematic, neuromuscular, and coordinative determinants associated with performance, comparing the kinematic behavior of the swing with the Driver and the 7-iron in elite under-18 golfers, analyzing the role of the X-Factor in relation to swing speed, and discussing practical implications for training and equipment selection. The findings confirm that performance in golf depends on the integration of multiple biomechanical determinants and that this integration must be interpreted in light of the athlete's developmental stage and the mechanical demands of the club used.

In conclusion, the golf swing in elite youth players should be understood as a coordinated, adaptive, and developmentally sensitive movement. The Driver and the 7-iron impose different mechanical constraints, but skilled young golfers appear capable of adapting their posture and velocity production while maintaining a stable temporal organization. The X-Factor is relevant for understanding pelvis-trunk interaction, but it should not be treated as an isolated performance target. For coaches, practitioners, and researchers, the main implication is that youth golf development should prioritize coordinated movement organization, individualized progression, appropriate physical preparation, and equipment suited to the athlete's characteristics. This integrated approach may support more effective, consistent, and safe performance development in young golfers.

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