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Key Points

- The modern golf swing is often promoted over the more relaxed classic swing, as it is believed to utilise elastic energy stored in skeletal muscles to increase power.
- The current literature provides conflicting evidence regarding the potential performance benefits associated with increasing muscle stretch during the modern golf swing.
- While this emphasis on increasing muscle and joint loads is thought to contribute to golfrelated low back injuries, there is currently limited evidence to support this notion.

Abstract

The modern golf swing is a complex and asymmetrical movement that places an emphasis on restricting pelvic turn, while increasing thorax rotation during the backswing to generate higher clubhead speeds at impact. Increasing thorax rotation relative to pelvic rotation preloads the trunk muscle by accentuating their length and allowing them to use the energy stored in their elastic elements to produce more power. As the thorax and pelvis turn back towards the ball during the downswing, more skilled golfers are known to laterally slide their pelvis toward the target, which further contributes to final clubhead speed. However, despite the apparent performance benefits associated with these sequences, it has been argued that the lumbar spine is incapable of safely accommodating the forces they produce. This notion supports a link between the repeated performance of the golf swing and the development of golf-related low back injuries. Of the complaints reported by golfers, low back injuries continue to be the most prevalent, but the mechanism of these injuries is still poorly understood. This review highlights that there is a paucity of research directly evaluating the apparent link between the modern golf swing and golf-related low back pain. Furthermore, there has been a general lack of consensus within the literature with respect to the methods used to objectively assess the golf swing and the methods used to derived common outcome measures. Future research would benefit from a clear set of guidelines to help reduce the variability between studies.

1. Introduction

The golf swing is a precise movement, comprised of a complex sequence of events that are ideally brought together at the point of impact to meet the main requirements of an effective golf swing; distance and direction [1-6]. Assuming that a golfer strikes the ball accurately, the distance that the ball travels will be a function of the velocity of the clubhead at the point of impact; however variations in launch angle and spin resulting from different club use, can also contribute to this factor [1, 7-12]. Although the golf swing may appear to be a benign activity, significant physiological effort and precise neuromuscular control is required to accelerate the clubhead to more than 160 km/h in 1/5th of a second [4, 13-17]. When considering that this movement can be performed more than 50 times during a round or up to 300 times during a typical practice session [13, 18], it is not surprising that the repeated performance of the golf swing is considered one of the primary causes of low back injuries in golfers (Table 1) [13, 15, 19-21]. Research has consistently reported that the lower back is the most common site of injury for male golfers [22-25] and the second most common site for female players [26-28]. Furthermore, low back injuries account for up to 55% and 35% of the golf-related injuries developed by professional and amateur golfers, respectively [22, 26, 29-35].

Insert Table 1 about here.

Given that the vast majority of golf-related low back injuries are attributed to poor swing mechanics or overuse [30], the development of effective golf-specific interventions requires clinicians and coaches to not only understand the movement and muscle firing patterns associated with the swing, but also to appreciate the physical stresses it places on the body [15, 28, 36, 37]. As such, the purpose of this review was to consolidate the literature concerning the mechanical and neuromuscular characteristics of the golf swing and to

summarise the existing research concerning the effects of low back pain (LBP) on the swing mechanics and muscle recruitment strategies associated with this activity.

2. A kinematic description of the modern golf swing

The original or *classic* golf swing begins with a long backswing that involves the pelvis and thorax turning through equally large ranges of motion (Figure 1a) and finishes with the pelvis and thorax in a relaxed and upright position that is perpendicular to the target (i.e. the flag) [24, 28, 29, 38]. However, over the past 60 years, the classic swing has evolved to allow golfers to maximise the benefits of equipment enhancements and thus facilitate longer drives and better overall performances [28, 29, 38]. In contrast to the smooth and rhythmic classic swing, the *modern* golf swing (Figure 1b) stresses the muscles and joints of the spine to generate a more powerful and effective movement [11, 24, 28, 29]. When analyzing the golf swing, coaches and researchers generally divide the movement into four phases that include the; i) address; ii) backswing; iii) downswing; and iv) follow-through [37, 39]. While this section outlines the movement patterns that characterise each of these phases, it is important to consider that different golfers may adopt different techniques to achieve a similar outcome [40-44]. In fact, research has suggested that skilled players often demonstrate considerable movement variability during many stages of the golf swing, but it is their capacity to maintain consistent clubhead dynamics at impact that separates them from less skilled players [45].

Insert Figure 1 about here

2.1 The address

The address (pre-swing) phase is an important component of the golf swing, as it is allows the golfer to position themselves to ensure a stable foundation from which to generate power throughout the swing [46, 47]. For the modern golf swing, ball address typically involves the

golfer standing with their feet approximately shoulder width apart, with their knees bent 20-25°, their trunk flexed to approximately 45° and their weight evenly distributed over their feet [1, 37, 47]. The trunk, hip and knee flexion that occurs during this phase brings the centre of gravity closer to the base of support, which ultimately flattens the arc of the swing and improves the overall stability of the golfer throughout the movement [47]. Golfers also tend to angle their lead foot (left in right-handed golfers) about 20-30° toward the target during ball address, which is believed to facilitate pelvic rotation about the hip joint and reduce torsional loads on the spine during the downswing [37, 48].

2.2 The backswing

The backswing commences when the clubhead begins to move away from the ball and serves to optimally position the golfer to execute a powerful downswing [39, 49, 50]. The initiation of this phase is facilitated by an anterior shear force produced by the trail foot (right in right-handed golfers) and a posterior shear force produced under the lead foot, which collectively produce a clockwise torque that rotates the pelvis and shifts the body's weight towards the trail foot [39, 46, 47, 51]. During the backswing, the movement patterns of the trail shoulder are characterised by a combination of abduction, flexion and external rotation, while the lead shoulder adducts, flexes and internally rotates [52-54]. At the top of the backswing, the lead arm is fully extended and the upper thoracic spine is rotated, such that its posterior aspect is facing the target [47-49]. Unlike the classic swing, however, the modern swing places a heavy emphasis on restricting pelvic rotation during the backswing (40-50°), whilst allowing the thorax to rotate through a range of motion that is approximately double that of the pelvis (90-100°) [11, 38, 55-57]. The restriction of pelvic turn relative to thorax turn is based on the notion that the torso must be 'torqued' as much as possible during the backswing to allow the body to store energy that can be released during the downswing [4, 39, 49, 55, 58]. By

'torquing' the torso, the muscles surrounding the hips (e.g. gluteus maximus), trunk (e.g. abdominal obliques, latissimus dorsi) and upper extremities (e.g. trapezius, rhomboids, pectoralis major) perform an eccentric contraction before they undergo a concentric contraction at the initiation of the downswing [1, 19, 47-49, 59]. This movement sequence is commonly referred to as the stretch-shorten cycle (SSC) and is considered to produce a more effective and efficient muscle contraction, as it allows the muscles to perform more positive work than would be possible with a concentric contraction alone [60]. However, the efficacy of the SSC is suggested to be proportional to the speed of the eccentric contraction and inversely proportional to the time that lapses between the eccentric and concentric components [1, 60]. Enoka [60] hypothesised that an increased pause between the eccentric and concentric phases results in the detachment of a greater number of cross-bridges within the muscles, which effectively reduces the muscle's stretch. Some support for the efficacy of the SSC in the golf swing has been provided in previous research, which suggested that a larger angle of separation between the pelvis and upper thorax (referred to as the X-factor) resulted in an increased driving distance in professional golfers [61]. Furthermore, golfers who produced higher ball velocities were shown to have significantly greater X-factor values than golfers who produced low to medium ball velocities [62]. Despite these findings, research comparing male and female golfers has reported that both genders achieve similar Xfactor values at the top of the backswing [45, 54], despite females achieving greater pelvic and upper thorax rotation at this point [54] and male golfers achieving higher clubhead velocities [45, 54]. Similarly, separate research has reported no significant differences in Xfactor values between expert and experienced golfers [9, 63] or amateur and professional golfers [64], suggesting that the magnitude of this measure at the top of the backswing may not be an important performance indicator for these populations [20, 63-65]. Given these findings, it is clear that the evidence regarding the importance of the X-factor is conflicting and a major contributing factor to this seems to be a general lack of consensus regarding the best method to use to derive pelvic and thorax rotation and, subsequently, this outcome [65, 66]. For example, much of the existing research [53, 62, 63, 67-69] has described thorax rotation as the rotation of a vector connecting joint markers positioned on the lateral border of the acromion processes. However, it is evident these markers may move throughout the golf swing due to factors that are not specifically related to shoulder joint motion. In fact, research has shown that this approach may lead to highly variable and inaccurate measures of thorax rotation, particularly when the trajectories of these joint markers are influenced by scapula retraction and/or protraction; such as that reported at the top of the backswing [70]. Therefore, while thorax and pelvic motion are strongly coupled throughout the golf swing, future research must seek to develop and implement standardised methods for measuring these kinematic characteristics to improve the overall quality of the research in this area.

2.3 The downswing

Early research modeled the downswing as a planar double pendulum, which comprised an upper segment representing the arms and a lower segment representing the club [71]. The upper segment pivoted at a central hub that was approximately located between the shoulders, whilst the lower segment was prevented from moving more than 90° either way by a hinge system that interconnected the two segments at the hands and wrists [8, 72]. Although Cochran and Stobbs [71] believed this model (Figure 2) was a good mathematical analogue of the professional golfer's downswing, several researchers have since improved this model by allowing the hub to accelerate both horizontally and vertically [73], including a third segment representing the trunk [74] and incorporating more realistic muscle dynamics [75]. Nevertheless, while some research has demonstrated that it is possible to fit the downswing of some experienced golfers to a single plane [76], others have shown that neither the lead arm

nor the club fit a fixed plane during the downswing and, hence, research incorporating such models should be considered with caution [77].

Insert Figure 2 about here

While the thorax and club continue to turn away from the target, the downswing is initiated by a forceful contraction of the hip and knee extensors on the trail side (right in right-handed golfers), which serves to redirect the movement and shift the body weight back toward the lead leg. During the golf swing, the lower limbs contribute more than 30% of the body's total work [36] and research shows that golfers who complete a greater amount of lower limb work are capable of achieving greater clubhead velocities at impact [78]. The powerful extension of the trail leg causes the pelvis to forcefully slide in a lateral direction towards the target, while also rotating towards an open position to face the flag [39, 46, 47, 50, 55, 58, 79]. As the pelvis continues to rotate, the thorax, arms, wrists and club unwind in a sequential fashion throughout the downswing [1, 23, 39-41, 47, 58, 80, 81]; adhering to the summation of speed (or summation of velocity) principle [82]. This progression of motion from proximal to distal segments, often referred to as 'leading with the hips' in golf, was observed in 75% of skilled golfers [67] and is suggested to further accentuate the stretch of those muscles involved in the SSC throughout the swing. This notion is supported by research showing that while the Xfactor at the top of the backswing was comparable between amateur and professional golfers, the change in X-factor between the top of the backswing and the peak value achieved during the downswing (referred to as X-factor stretch) was greater in professional players [83]. The authors noted that this difference was due to the fact that more skilled players had a tendency to 'lead with the hips' during the downswing, while less skilled players did not [63, 83]. The successful execution of this movement pattern relies upon a well-balanced combination of axial pelvic rotation and lateral pelvic slide; both of which have traditionally been considered equally important [84]. However, according to Seaman [49] and Seaman and Bulbulian [48], lateral displacement of the pelvis is likely to be a greater contributor to the power generated during the early stages of the downswing, as there are no muscles purely known for their function as medial hip joint rotators and those involved in lateral hip rotation are typically small and incapable of generating explosive forces.

As the pelvis continues to rotate and laterally slide, the club and lead arm (left in right-handed golfers) form an angle of $\leq 90^{\circ}$ at the wrists [71, 85]. When this angle is less than 90° , acceleration of the lead arm in a forward and downward direction facilitates the acceleration of the golf club in the same direction due to a reduced moment of inertia [39, 67]. The upper body and the club continue to accelerate throughout the downswing, until the club reaches an approximately horizontal position (80-100 ms prior to impact). At this point, the lead forearm supinates and the trail forearm pronates, while the trail wrist moves towards a flexed position [39, 54, 75, 85, 86]. During this phase, the lead and trail wrists also move rapidly from radial deviation to ulnar deviation; a movement sequence that coaches have traditionally referred to as wrist uncocking [54, 86]. Early golf research based on two-dimensional descriptions of the golf swing demonstrated that uncocking the wrists too early during the downswing decelerates the arms and the club, ultimately reducing clubhead velocity at impact [47, 87]. Therefore, it is commonly suggested that golfers attempt to delay the uncocking of the wrists during the downswing phase, as this facilitates the achievement of greater segmental angular velocities at impact [39, 72, 85, 88]. Although mathematical models of the golf swing have provided support for the notion of delaying wrist uncocking [89], it should be noted that the description of wrist motion during the swing is still often limited to changes in radial to ulnar deviation and, hence, largely overlook the other degrees of freedom afforded to this joint.

2.4 The follow-through

The downswing is completed with ball impact, at which point the pelvis has turned through a range of about 90° to be 40-45° beyond the line of the target, whilst the upper thorax has turned through a range of approximately 105° to be 20-25° past the target line [39, 55]. Following impact, the upper thorax turns through at least 120° and the golfer concludes with their vertebral column in a hyper-extended position, their trail shoulder (right in right-handed golfers) pointing towards the target, and their hands positioned high above their head. This posture is commonly referred to as the 'reverse C' position [15, 29, 38, 39, 48, 49]. While the speed of the movement steadily decreases following impact, previous research has argued that the skeletal and soft tissue structures of the spine may not be able to safely accommodate the large range of movement [48] and high spinal loads [28, 38] that occur at impact and throughout the follow-through. For example, a combination of pelvic and spinal rotation and scapula protraction/retraction allows the upper body to rotate over 120° during this phase. However, due to the sagittal orientation of the lumbar facets, the lumbar spine's contribution to this rotation is limited to as little as 1° per segment (approximately 5-6° total) [90, 91]. Furthermore, between impact and the end of the follow-through, the lumbar spine experiences large peaks in lateral flexion and anteroposterior shear forces, as well as compressive and torsional loads [28, 92]. Considering that the anteroposterior and compressive loads associated with the golf swing reach values that are near to the known tolerance limits of some vertebral structures [28], it is not surprising that anecdotal evidence suggests that up to 41% of low back injuries are sustained around impact and during the early follow-through phase of the golf swing [30, 68, 93].

3. The impact of low back pain on the kinematics of the golf swing

Although the incidence of golf-related low back injuries has been adequately researched and presented within the past and current literature [18, 22, 30, 94-96], there have been very few researchers that have assessed the underlying mechanisms of the disorder [97]. To date, only four studies [68, 97-99] and three case reports [22, 69, 100] have assessed the kinematics and range of motion characteristics of golfers suffering with LBP. In an investigation conducted by Lindsay and Horton [97], a device known as the lumbar motion monitor was used to assess the three-dimensional motion of the trunk during the performance of the golf swing in golfers with LBP. According to the authors, injured golfers did not differ significantly from uninjured golfers for address position, trunk flexion angle or lateral flexion towards the trail side. However, injured golfers have been shown to have greater lateral flexion towards the lead side [97, 98] and less trunk rotation toward the trail side during the backswing [98] and consistently rotate their trunk through a greater range of motion than that achievable during a maximum voluntary effort [97]. With respect to segmental speeds during the swing, golfers with LBP are reported to achieve similar trunk extension velocities [97], right-side lateral bending velocities [97] and axial trunk rotational velocities [68, 97, 98] compared with their asymptomatic counterparts. However, lateral flexion velocities towards the lead side and trunk flexion velocities are reported to be significantly greater for golfers with LBP [97]. Despite these differences, however, it is worth noting that right-side trunk rotation, lateral trunk flexion angle (and velocity) towards the lead side and trunk flexion velocity all peak during the backswing, which is typically not reported to be a high-risk component of the golf swing [30].

Nevertheless, radiographic findings suggest that golfers demonstrate a higher rate of bone spurs (osteophytes) and degenerative changes to the trail side of the lumbar facets, when compared with non-playing controls [29, 101]. According to Sugaya and colleagues [29, 101], the distinct laterality of these changes provides evidence for the damaging effects of the asymmetric motion of the modern golf swing. On the basis of these findings, Sugaya et al. [102] proposed a new measure dubbed the crunch factor, which was intuitively devised based on the knowledge that both lateral trunk flexion toward the trail side and axial trunk rotational velocity reach their peak shortly after ball impact. The authors defined the lumbar crunch factor as the instantaneous product of these two kinematic quantities and hypothesised that the combined effect of these factors contributed to degenerative changes and injuries to the lumbar spine. As such, it has been suggested that the crunch factor may be a useful objective measure for comparing the mechanics of the trunk in injured and healthy golfers [29]. Empirical evidence demonstrates that peak crunch factor values occur about 52 ms following ball contact, which provides some support for the possible value of this measure in assessing injury potential in golfers [103]. However, to date, only two independent studies [68, 97] have presented data for the crunch factor in a population of golfers specifically suffering with LBP. The results of these studies demonstrated that golfers with LBP did not demonstrate significantly different peak crunch factor values than asymptomatic controls, which suggests that while the fundamental concepts that underpin this measure may be sensible, other factors are likely responsible for the development of low back injuries in this population.

Given the general lack of differences in the movement patterns of symptomatic players, researchers have sought to evaluate whether deficits in joint mobility may play a role in exacerbating the stresses placed on the body during the golf swing. While some of this research suggests that golfers with LBP do not differ from asymptomatic players with respect to joint mobility [98], other research [99] and separate case reports [22, 69, 100] suggest that limitations in hip and/or spinal mobility may contribute to symptoms of LBP. Vad et al. [99]

assessed hip joint range of motion for a group of golfers with LBP and demonstrated that these golfers had a reduced capacity to internally and externally rotate the lead hip (left in right-handed golfers) during the swing. Such range of motion deficits have been suggested to result from capsular contracture, which can occur in response to micro-trauma caused by the repeated performance of stressful movements [99, 104]. It was postulated that this reduced capacity to rotate the lead hip places a heavier emphasis on the spinal segments to complete the rotation associated with the movement [99, 104], effectively increasing the load on the lumbar facet joints that resist axial motion in this spinal region [105]. However, two separate case reports have provided a small amount of evidence to suggest that golfers with chronic LBP may have reduced spinal flexibility that significantly restricts their ability to rotate [22, 100] and flex their trunk [22]. Hence, the reduced mobility that is evident in the hip and lower spinal regions may reduce the body's capacity to attenuate movement-related forces and lead to larger mechanical loads being placed on the lumbar spine [106]. Previous research supports this notion by demonstrating that poor spinal mobility was linked with lumbar spinal stresses that were up to 100% greater than those expected under normal conditions [107]. While case studies suggest that individualised conditioning programs that seek to improve trunk and/or hip range of motion may contribute to the alleviation of LBP in individual players [22, 69, 100], it remains unclear whether these findings are transferrable to the wider golfing community.

4. An electromyographic description of the modern golf swing

The modern golf swing is a complex, asymmetrical movement that is not only physically demanding, but is heavily reliant on the powerful and precisely-timed contraction of many of the body's skeletal muscles [108, 109]. To examine the patterns of muscle recruitment during the golf swing, researchers often employ electromyography (EMG) [3, 69, 110, 111], as this

procedure provides insight into the degree and timing of a muscle's activation [112, 113]. The recorded EMG signal essentially provides the researcher with a graphical representation of the electrical activity occurring within a contracting muscle, which allows them to identify the onset and cessation of activity, whilst also providing information regarding the amplitude of the activation [113]. In the past, researchers have used surface or fine wire EMG to examine the muscle activity patterns of the shoulders [114-119]; trunk [3, 19, 69, 92, 110, 111, 120-122]; hips and knees [123, 124]; and neck and forearms [114, 125, 126] during the performance of the golf swing. The following sections consolidate the existing research to provide a comprehensive summary regarding the contribution of different muscle groups to the performance of the right-handed golf swing.

4.1 The address

Some of the first research to examine myoelectric activity during the golf swing was conducted with healthy male [116, 119-121] and female golfers [119]. Subsequent research has built upon this body of knowledge and has helped to develop a sound scientific understanding of the ways in which the muscles of the body are recruited during the performance of this movement [115, 123, 124]. As there is essentially no movement during the address phase, very little research has reported on the myoelectric patterns during this phase of the swing. However, research has reported small levels of activity bilaterally for the erector spinae [110, 124] and the anterior deltoid, upper trapezius and biceps femoris on the lead side (left in right-handed golfers) during this phase, whilst the other muscles of the trunk and lower extremity were relatively inactive [124].

4.2 The backswing

Initiation of the backswing is assisted by the activation of the lead external and trail internal oblique muscles, which facilitate the clockwise rotation of the trunk away from the target and

effectively move the clubhead away from the ball [3, 22, 38, 48, 120, 121, 127, 128]. The lead rectus abdominis and paraspinal muscles are also reportedly active during this phase and likely contribute to the left-side lateral trunk flexion that characterises the mid to late stages of a right-handed golfer's backswing [28, 49, 127]. However, according to Bogduk [91] the abdominal oblique muscles comprise both horizontally- and vertically-aligned muscle fibres, which are suited to different types of trunk motion. When the abdominal oblique muscles are activated, both the horizontally- and vertically-aligned muscle fibres are contracted, which will result in trunk flexion and rotation in the absence of any other muscle control. Therefore, the paraspinal muscle activity reported during the early backswing is more likely to counteract the flexor moment created by the abdominal obliques, rather than contribute to trunk rotation [49]. During the early stages of the backswing the activity of the trail erector spinae increases and proceeds to fire simultaneously with the lead erector spinae throughout the remainder of the backswing, emphasising the role of these muscles as stabiliser of the trunk [28, 69, 120, 121]. As the trunk continues to rotate away from the target, the trapezius, levator scapulae and rhomboid muscles on the trail side are activated to facilitate scapula retraction and elevation [115, 129]. These movements of the trail arm are accompanied by simultaneous activation of the lead pectoralis major and anterior deltoid, which promote scapula protraction and internal rotation and assist with positioning the hands and club above the head at the end of this phase [116, 130]. Throughout the backswing, the semimembranosus and biceps femoris muscles demonstrate mild levels of activation bilaterally, as they both resist knee extension [123, 124, 129, 130]. The importance of this function should not be underestimated, as the maintenance of knee flexion throughout the backswing is suggested to permit the trunk to move through a larger range of motion and allow for better dissipation of joint loads [47].

4.3 The downswing

The downswing is initiated by a forceful contraction of the gluteus maximus, gluteus medius, biceps femoris and semimembranosus of the trail leg, which act to extend and push the hip forward to initiate a counter-clockwise rotation of the pelvis [37, 120, 123, 124, 129, 130]. The forceful contraction of the hip extensors on the trail side is complemented by a concurrent contraction of the adductor magnus on the lead side, which assists pelvic rotation by pulling the lead leg backwards and towards the midline of the body [123, 130]. During the very early stages of the downswing, erector spinae activity on the trail side is increased [69, 121, 131, 132], which is believed to be required to counteract the rotational and gravitational forces acting on the body during this phase and ensure that the body's position is maintained [121]. As the body begins rotating back towards the target, the weight is shifted from the trail leg to the lead leg [51], which requires an increase in knee extensor activity to resist knee flexion and thus, provides a stable foundation upon which the pelvis and trunk can rotate [123, 130]. Shortly after the downswing is initiated, the latissimus dorsi on the lead side is activated to bring the left arm down [131], while increased activity of the trail external oblique and lead internal oblique serve to rotate the trunk toward an open position [3, 28, 38, 120, 121, 128, 129, 131, 132]. The maximal contraction of the abdominal oblique muscles is then accompanied by the bilateral contraction of the erector spinae, which again, act to stabilise and protect the spine from injury resulting from the excessive flexion and rotational forces produced by the oblique muscles [38, 48, 121, 128, 131-133]. Additionally, the levator scapulae, rhomboids and trapezius muscles in the lead arm are also very active during the early stages of the downswing, as they act to retract and elevate the lead scapula [115, 124, 129]. The retraction and elevation of the lead scapula is accompanied by protraction and internal rotation of the trail shoulder, which is initiated by the pectoralis major and the serratus anterior [37, 116, 124, 129, 130, 132]. Collectively, the muscle activity around the lead and trail shoulders during the downswing contributes to bringing the arms and club back across the body. Control of the wrist and forearm during the downswing is facilitated by the bilateral activation of the flexor carpi radialis and the flexor carpi ulnaris, which are activated throughout the downswing to overcome the inertia of the club and accelerate it downwards and forwards towards the ball [126]. During the mid to late stages of the downswing, the bilateral activity of the extensor carpi radialis brevis also increases [126]. This increase in extensor carpi radialis brevis activity is indicative of the concentric contraction of this muscle in the lead (left arm in right-handed golfers) and its eccentric contraction in the trail arm to resist the natural tendency for the wrist to uncock during this phase [126]. As the club approaches impact, the lead and trail pectoralis major are both activated maximally [132], which may serve to stiffen the upper body in preparation for impact of the clubhead on the ball. Alternatively, the increased activity of the lead pectoralis major during the downswing may represent an eccentric contraction of this muscle to help stabilise and control the external rotation and retraction of the lead shoulder [129].

4.4 The follow-through

From impact through to the late follow-through, the gluteus medius on the lead side (left in right-handed golfers) demonstrates a low, but steady level of activity, as it assists with sliding the hips laterally throughout this phase [123, 124]. Similarly, the gluteus medius on the trail side continues to demonstrate high activity levels immediately following impact, as it abducts and extends the trail hip to assist with pelvic rotation during the early stages of the follow-through [123, 124, 129]. However, as the golfer nears the completion of the follow-through, pelvic rotation slows and the activity of the trail gluteus medius muscle also decreases [123, 124]. Meanwhile, the lead biceps femoris and vastus medialis muscles continue to co-contract throughout the follow-through phase, as they continue to provide a stable foundation

to complete the counter-clockwise rotation of the body [123, 124, 129]. The rotation of the trunk is facilitated by the continued activity of the lead internal oblique and the trail external oblique muscles, which demonstrate only mild tapering in activity levels following ball impact [3, 120, 121]. Additionally, the myoelectric activity of the erector spinae is suggested to decrease shortly after impact, with the lead side often showing higher levels than the trail [69, 120, 121, 124]. Like the abdominal oblique muscles, the levator scapulae, rhomboids and trapezius muscles on the lead side and the pectoralis major and serratus anterior on the trail side demonstrate only slight reductions in activity levels during early follow-through [115, 116, 129]. The notable activity demonstrated by these muscles is associated with their respective roles in elevating and retracting the lead shoulder and protracting and internally rotating the trail shoulder as the arms and club move through the follow-through [115, 116, 129]. The activity of these muscles continues to decrease throughout the remainder of the swing, as the lead shoulder is externally rotated and elevated and the trail shoulder is internally rotated to assist in positioning the arms and golf club above the head at the end of the movement [115, 116]. Similarly, the bilateral activity of the erector spinae and the trail external oblique continues to decrease as the follow-through progresses, whilst the activity of the lead external oblique remains similar to that of the early follow-through [120, 121]. According to Watkins and colleagues [120], the significance of the continued lead-side external oblique activity during this phase of the swing is suggested to be related to this muscle's role in decelerating the rotation of the trunk.

4.5 Summary

From this myoelectric description of the golf swing, it is evident that the posterior trunk muscles are bilaterally activated throughout most of the golf swing to maintain the integrity of the spine (i.e. stabilise) and protect its structures from potential damage. However, it is

important to acknowledge that some literature has suggested that higher levels of trunk muscle activity during the performance of the golf swing may be deleterious to the structures of the lower back in golfers [110, 131]. A previous review provided some support for this notion, suggesting that greater muscle forces are required to displace a stiffer spine, which could lead to injury in some specific situations [134]. Given the apparent importance for golfers to demonstrate precisely timed and appropriately sized muscle contractions throughout the golf swing, researchers have recently started to investigate whether golf-related LBP may be caused by neuromuscular dysfunction that alters the muscle recruitment strategies used by these players.

5. The impact of low back pain on the neuromuscular system of golfers

As there have been very few attempts to assess the swing characteristics of golfers with LBP, it is not surprising that very little attention has been given to the ability of these golfers to coordinate the different muscle groups to bring about a safe and effective swing [3, 120]. However, due to the association between efficient muscle firing patterns and superior muscle coordination, Watkins and colleagues [120] postulated that there may be differences between injured and uninjured golfers with respect to the muscle firing sequences that they use to perform the golf swing. Similarly, Hubley-Kozey and Vezina [135] indicated that whilst individuals with LBP were capable of performing a set of clinical tasks correctly with respect to specific movement criteria, they achieved this result using different muscle recruitment strategies. Furthermore, previous research suggests that in the presence of acute and chronic LBP, the function of the transversus abdominis and lumbar multifidus is preferentially affected when compared with their superficial counterparts [136-138]. Based on such evidence, a number of small studies [3, 110, 111, 139-142] and case reports [22, 69] have

sought to identify possible differences in the muscle recruitment strategies and muscle endurance characteristics of golfers with and without LBP.

In their assessment of a professional golfer suffering with chronic LBP, Grimshaw and Burden [69] reported a reduction in the activity of the lumbar erector spinae during the downswing phase following a 3-month period of coaching and muscle conditioning. The authors attributed this change to the coaching, which increased the range of pelvic rotation during the backswing and reduced the eccentric loading of this muscle during the latter stages of this phase [69]. In contrast, research involving skilled golfers with and without LBP demonstrated that symptomatic players had significantly reduced levels of erector spinae activity, but greater external oblique activation compared with asymptomatic controls [110]. Interestingly, the ratio of external oblique to erector spinae activity at impact was almost 2.5 times greater for the low-handicap golfers with LBP compared with the asymptomatic players (2.5 vs. 1.1). The authors argued that while reduced erector spinae activity may correspond with lower compressive forces and reduced injury risk, it may also reflect a neuromuscular deficit that leaves the spine inadequately stabilized at impact, where joint loads are known to be high [28, 92]. Separate research investigating the superficial abdominal muscles in golfers with and without chronic LBP indicated that the amplitude of rectus abdominis, external oblique and internal oblique activity did not differ significantly between symptomatic and asymptomatic players [3].

In addition to the differences observed in the amplitude of trunk muscle activity, research has also highlighted a number of inconsistencies in the contraction onset and cessation timings of the superficial trunk muscles [3, 111]. In a study conducted by Cole and Grimshaw [111], golfers with LBP activated the lumbar erector spinae significantly earlier than asymptomatic players in preparation for the backswing. Given that deep postural muscles, such as the multifidus, are preferentially affected in patients with LBP [136-138], the authors suggested that the earlier activation of the superficial erector spinae indicated that these muscles are playing a greater role in stabilising the spine in the injured players [111]. This notion is supported by previous research which has shown that golfers with LBP have reduced trunk muscle strength [141] and/or deep trunk muscle endurance [139, 142] compared with asymptomatic players. In contrast to the earlier activations reported for the posterior trunk muscles, Horton and colleagues [3] reported that the lead external oblique (left in righthanded golfers) was activated significantly later during the backswing in golfers with LBP when compared with asymptomatic controls. According to Hubley-Kozey and Vezina [135], such delays in onset may provide evidence for an impaired feed-forward control strategy in LBP patients; that is these individuals react to perturbations, rather than anticipate them. Importantly, however, the differences reported in these studies were confined to the backswing, which is not typically considered a high risk phase of the movement [28-30, 93]. As such, while these differences in muscle activation may provide evidence to suggest altered neuromuscular control in the injured golfers, it is unclear whether they provide insight into the possible cause of golf-related LBP. Nevertheless, Hodges [143] and O'Sullivan et al. [144] reported that the reduced functionality of the deep trunk muscles may require synergists, such as the rectus abdominis and erector spinae, to be more heavily involved during dynamic tasks to ensure that spinal stability is maintained. Furthermore, empirical evidence suggests that the function of the deeper trunk muscles is not spontaneously recovered following the cessation of painful symptoms [136]. While a small number of case reports suggest that improving the strength and control of these muscles can assist with alleviating symptoms of LBP in golfers [22, 69], larger prospective studies are needed to determine the potential efficacy of this approach for minimizing the risk of LBP in golfers.

6. Conclusion

The evolution of the modern golf swing over the past 60 years has led to the promotion of a movement sequence that places a large emphasis on restricting pelvic rotation while allowing the upper thorax to rotate through a range that is almost twice that of the pelvis. While this technique is suggested to increase power by capitalising on the elastic properties of skeletal muscle, there are conflicting findings within the literature regarding the potential benefits of increasing muscle stretch on overall golfing performance. These discrepancies are largely attributable to a lack of consistency between studies with respect to their definition and calculation of common performance-based measures. These findings highlight the need for a recommended and universally-accepted set of outcomes that can be easily utilised within this field.

A second key finding of this review was that there is currently a shortage of well-powered studies seeking to better understand the underlying mechanisms of golf-related low back injuries. Moreover, the existing cross-sectional literature presents conflicting arguments regarding differences in the movement patterns and muscle recruitment strategies of golfers with LBP. As such, larger-scale longitudinal studies should be considered for future research seeking to develop a better understanding of the role(s) that swing mechanics and muscle activity patterns might play in the development of low back injuries in golfers. Without such research, it is likely to be difficult to effectively translate the findings of research into coaching and clinical practices.

Finally, research seeking to gain insight into possible mechanisms of golf-related low back pain has generally focussed on changes in the movement patterns of individual segments or changes in neuromuscular function. As such, there is a clear need for future research to build on this existing knowledge to establish whether low back injuries influence inter-segmental coordination, spinal loading patterns and/or coordinated neuromuscular function.

Compliance with Ethical Standards

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Figure Captions

<u>Figure 1</u>: Diagrammatical representation of the; (a) classic golf swing; and (b) modern golf swing. The darker and lighter ellipses portray the orientation of the upper thorax and pelvis respectively at each of the stages of the golf swing. (Image drawn based on information presented by Hosea & Gatt [28], pp. 40-41)

Figure 2: The components of the double pendulum model in two positions throughout the swing; (a) the early downswing; and (b) mid-downswing. (Image drawn based on information presented by Cochran & Stobbs [84], p.10)

| Study | Year | Population | Sample Size | Total Number of Injuries | % Lower Back Injuries |
|-------------------------|------|--------------|-------------|-----------------------------|--------------------------|
| McCarroll et al. [26] | 1990 | Amateur | 1144 | 708 | 34.5% |
| Batt [27] | 1992 | Amateur | 193 | 61 | 21.3% |
| Burdorf et al. [31] | 1996 | Amateur | 196 | 62 | 31.6% |
| Thériault et al. [32] | 1996 | Amateur | 528 | 198 | 17.2% |
| Finch et al. [33] | 1999 | Amateur | 34 | - | 24.0% |
| Gosheger et al. [95] | 2003 | Amateur | 643 | 527 | 15.2% |
| McHardy et al. [30] | 2007 | Amateur | 1634 | 369 | 24.9% |
| McHardy et al. [34] | 2007 | Amateur | 588 | 93 | 18.3% |
| Mean | | | | | 23.4% |
| 95% Confidence Interval | | | | | 18.6 - 28.1% |
| McCarroll & Gioe [35] | 1982 | Professional | 226 | 393 | 23.7% |
| Sugaya et al. [29] | 1999 | Professional | 283 | 281 | 54.8% |
| Gosheger et al. [95] | 2003 | Professional | 60 | 110 | 21.8% |
| Mean | | | | | 33.4% |
| 95% Confidence Interval | | | | 12.5 - 54.4% | |

Table 1: Summary of the epidemiological literature on the prevalence of low back injuries in amateur and professional golfers



b



b