Knee Mechanics in the Golf Swing and the Potential Risk for Injury to the Anterior Cruciate Ligament and Other Structures: A Review

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Funding The authors received no financial support for the research, authorship, or publication of this article.

Conflict of Interest The authors report no conflicts of interest.

Acknowledgements We would like to acknowledge The University of New Mexico's Men's Golf Coaching Staff, Glen Millican and Gustavo Morantes.

ABSTRACT

The aim of this study is to review the current literature on knee biomechanics during the golf swing, focusing on angles, forces, and moments seen in both the lead and trail limbs. The golf swing is described in terms of the backswing, downswing, and follow-through. Studies consistently show that the directional torque changes in multiple planes, and that both lead and trail knees face significant forces throughout the swing. The high rotational forces and repetitive loads experienced by golfers' knees pose a potential risk for injury. Fatigue failure to the anterior cruciate ligament (ACL) has been postulated to occur from cyclic stress below the ligament's ultimate strength with each swing. A better understanding of stresses on the ACL and on other structures of the knee can help sports medicine providers develop golf-specific injury prevention training programs, treat nonoperative golf-related injuries, and create postoperative rehabilitation and return-to-play protocols.

Keywords: Golf; Knee injuries; Biomechanics; Sports medicine; Rehabilitation

INTRODUCTION

Golf is a sport enjoyed by those of all ages and skill levels, with over 55 million people who play worldwide. It is typically considered a low-impact sport with little risk for knee injury.[1] It is regarded as a safe activity following total knee arthroplasty (TKA) regardless of laterality, although a significant rise in handicap is expected.[2] Due to social distancing and outdoor safety, golf has become increasingly popular for many since the onset of the Covid-19 pandemic.

Baker et al.[1] performed the first systematic review of knee injuries in professional and amateur golfers, and found the overall prevalence to be 3.0% to 18.0%. Injury prevalence was not dependent on skill level or sex; however, older players were at greater risk. Results suggest that the lead knee is subject to a higher magnitude of stress and more demanding motions than the trail knee. Details were not provided about the mechanism of injury, and most studies failed to report the type of knee injuries. Thus, it is difficult to attribute these injuries entirely to golf-related activity.[1] Case studies have provided some indication of the structures most susceptible to damage when playing golf, including osteochondral fractures of the patella, tibial stress fractures, failure of polyethylene knee arthroplasty components, and medial meniscus tears.[3-8]

Specific injury to the anterior cruciate ligament (ACL) while golfing has been theorized to result from repetitive stress over time, but there is a lack of literature exploring this idea. Although it may be rare to suffer an ACL injury while playing golf, many athletes recovering from ACL reconstruction (ACLR) or other knee procedures, including meniscal work and arthroplasty, hope to return to the golf course after surgery.[9,10] In a retrospective questionnaire of 93 golfers with an average age of 66, Jackson et al.[11] found the return-to-play rate after TKA to be greater than 94.0% at 8.7 years follow-up. Therefore, it is important to recognize which knee structures face the most stress and are at risk for injury to guide the development of sport-specific injury-prevention programs and postoperative rehabilitation protocols.

The purpose of this paper is to review the biomechanics of the golf swing, with particular focus on the potential effects of golf on ACL injury and rehabilitation after ACLR.

RESULTS

Golf Swing Knee Biomechanics

For right-handed golfers, the left knee is considered the lead knee, and the right knee the trail knee. The opposite is true for left-handed golfers. The motion around the knee joint is complex. Its stability derives from the bony geometry of the femur and tibia, active stabilization by surrounding muscles, and passive stabilization from ligaments and the joint capsule.[12] The ACL is recognized as the primary stabilizer to both anterior tibial translation and rotational knee loads.[12] The menisci, anterolateral ligament (ALL), and iliotibial (IT) band constitute secondary stabilizers.[12]

The commonly described phases of the golf swing include the back swing (from takeaway to the top of the back swing), downswing (from the top of the back swing to ball contact), and follow-through (from ball contact to finish).[10,13] The concept of "triggering" each shot with a small movement prior to the initiation of the swing complex has been popularized, but no known study has investigated the biomechanics of this added motion or its effects on the rest of the swing.[14] Several "triggers" have been described, all of which are memory tools designed to help make the swing more rhythmic and reproducible.[14] For example, Matt Wolff, a member of the Professional Golf Association (PGA) initiates his swing by rotating the hips anteriorly.[15] Two other PGA members, Rory McIlroy and Bryson DeChambeau, push into the ground with their lead leg right before starting the backswing.[16]

Changing angles and rotational moments related to knee flexion/extension (in the sagittal plane), adduction/abduction (in the coronal plane), and internal/external rotation (in the axial plane) are important to consider to understand forces seen by specific structures of the knee during each phase of the swing. A few studies have evaluated the kinetics and kinematics around the knee joint during the golf swing, the results of which are summarized in table 1. In addition to rotational torque around different axes, compressive, medial/lateral, and anterior/posterior forces have been reported.

It should be noted that the current literature regarding motion in the coronal plane consistently refers to knee position in terms of abduction and adduction. Specifically, the knee is in abduction when it is outside the hip and in varus. Conversely, when the knee is in valgus and more midline relative to the hip, it is in adduction (Figure 1). This review will use the same terminology. It should also be pointed out that most of the studies used a driver or 5-iron. This important difference in club selection should be kept in mind when interpreting the results. Significant differences in trunk, pelvis, hip, knee, and ankle sagittal plane joint angles were demonstrated between use of a driver and 6-iron by Severin et al.[17]Although not specifically evaluated in this study, these differences in swing mechanics may have a large effect on the forces about the knee.[17]

Backswing

During the backswing, studies consistently show the lead knee is positioned in flexion, adduction, and external rotation.[10,13,18] A maximum of 7.9° of tibial external rotation has been reported.[10] The knee flexion angle at set-up, right before the initiation of the backswing, is reported to be 18°+/- 12° by Murakami et al.[19] By the second half of the backswing, the lead knee sees abduction and external rotation moments in addition to a flexion moment.[10,13,20] The trail knee displays more extension, and this remains relatively constant throughout the entire backswing. The trail knee also displays slight abduction and increasing internal rotation (Figures 1a and 1b).[13] Heading toward the top of the backswing, the abduction moment increases in the lead knee, and decreases to almost zero in the trail limb. By the end of the backswing, the trail knee reaches its peak internal rotation (Figures 1c and 1d).[13] To conceptualize these rotation moments in the coronal and axial planes, it is helpful to look at the lead and trail leg of the right-handed golfer in Figure 1c. The lead knee is in an adducted position. The trail knee experiences internal rotation. At the end of the backswing, it is useful to visualize the trail leg resisting 'swaying' as the mechanism for internal rotation.

Downswing

During the first half of the downswing, both knees are in flexion, with the lead knee to a greater extent.[13] The lead knee experiences its maximum flexion at the beginning of the downswing, and this is reported to be approximately 43.7° by Purevsuren et al.[10] and 32.7° +/- 7.7° by Murakami et al.[19] During the second half of the downswing, both knees rapidly extend, with the lead knee beginning to straighten out just before the trail knee (Figure 1f).[13] At the same time, the lead tibia rapidly internally rotates while the trail tibia externally rotates at a similar rate.[13]

Carson et al.[13] found that the lead knee experiences its peak flexion moment about halfway into the downswing (1.30 Nm/Kg +/- 0.35 Nm/Kg), while the trail knee feels its peak extension moment at the same time (0.79 Nm/Kg +/- 0.22 Nm/Kg). Gatt et al.[18] reported a lead knee peak flexion moment of 20.8 Nm +/- 23.3 Nm and a trail knee peak extension moment of 58.6 Nm +/- 14.4 Nm, but they did not specifically indicate when these moments occurred. In contrast to Carson et al.[13], Purevsuren et al.[10] reported a peak flexion moment in the lead knee that did not occur until after ball-impact, at the beginning of the follow-through. Also in contrast to Carson et al.[13], Choi et al.[21] found the peak flexion moment in their cohort of skilled golfers to occur at ball-impact for the lead knee. In the trail knee however, Choi et al.[21] reported similar findings to Carson et al.[13], with the peak trail knee extension moment occurring during the downswing.

In the frontal plane, the lead knee rapidly shifts into abduction from the adducted position noted at the top of the backswing.[10,13] Gatt et al.[18] shows the trail

Table 1: Biomechanical Studies Assessing Forces and Moments on the Knee Joint During the Golf Swing

References	Cohort	Focus of Study	Findings and Conclusions
Gatt el al[18], 1998	13 healthy male golfers hit a five iron under two footwear conditions: spiked and spikeless golf shoes, $\bar{x}$ age 35 years old with no lower extremity joint injuries or abnormalities, handicaps 11.2	3D knee joint kinetics and kinematics of lead and trail limb to determine the peak forces and moments generated at the knee joint during the golf swing, in addition to studying whether footwear and skill level affect peak knee joint loads	-peak moment values were not high risk for traumatic knee injury in the healthy population but could be a concern during rehabilitation for ACLR -there is no difference in the knee joint kinetics between skilled and unskilled golfers, and the type of shoe worn did not significantly affect the mean peak knee joint forces -the downswing was the most stressful phase on the knee -the loads seen by the lead and trail legs are substantially different -maximum extension moment in the lead knee and maximum flexion moment in the trail knee occur during the downswing
Purevsuren et al[10], 2016	10 healthy male golfers with no musculoskeletal injury within the past year from the Korean Professional Golf Association, $\bar{x}$ age of 23.2 years old, $\bar{x}$ handicap 2.6, own driver used	3D knee joint kinetics and kinematics of lead limb during golf swing & ACL fatigue injury risk	-less knee flexion, greater internal tibial rotation, increased joint compressive force, and increased knee abduction moments seen during the follow-through phase are associated with increased loading of the ACL
Carson et al[13], 2020	10 professional male golfers from Great Britain/Ireland with $\bar{x}$ age of 32, handicap <4, driver used	3D knee joint kinetics and kinematics of lead and trail limb	-significantly higher net abduction moment was seen in the trail knee compared to lead knee, which could contribute to knee lateral compartment or ACL injuries - a positive correlation was noted between clubhead speed at ball contact and maximum joint moment -large knee joint moments may contribute to chronic knee injuries or exacerbate existing conditions
Lynn and Noffal[20], 2010	7 male and female collegiate golfers from Queen's University without history of chronic pain, major injury, or surgery to the lower limbs or low back, $\bar{x}$ handicap of 2.9, $\bar{x}$ age 21.3 years old, 5-iron used	Coronal plane knee moments during the golf swing for the lead knee in a straight and externally rotated foot position	- peak knee abduction moment is not affected by set-up position, but the peak adduction moment can be reduced by externally rotating the lead foot at set up - peak knee abduction moment magnitude was comparable to a drop jump landing, but 50% to 71% less than that of a side-step cutting maneuver - the magnitude of these moments is greater than those experienced during activities of daily living (i.e. gait & stair ascent)
Hooker et al[23], 2018	20 healthy golfers, driver used	- 3D biomechanical analysis of golf shots in various stance conditions: self-selected, bilateral 0° foot angle, bilateral 30° foot angle, wide stance width, and narrow stance width - analyzed knee adduction and abduction moments throughout swing in the above conditions	-30° lead leg foot angle and wide stance significantly decreased lead limb peak knee adduction moment compared to self-selected
Choi et al[21], 2015	18 skilled and 23 unskilled golfers, own driver used	Knee flexion and extension moments of the knee	-lead knee in the skilled group experienced its peak extension moment during the downswing and peak flexion moment at ball-impact -the trail knee in the skilled group mirrored the curve pattern of the lead knee through the entire swing -lead knee in unskilled group did not show distinct extension moment, but peak flexion moment occurred during the downswing in the trail knee

Key: $\bar{x}$ = mean

Figure 1: Knee Biomechanics of the Golf Swing

Backswing in the frontal plane (A) and sagittal plane (B):

Lead knee: *Slightly adducted (in valgus) in the frontal plan (A), flexed in the sagittal plane (B), with some external rotation in the axial plane. Abduction, external rotation, and flexion moments are seen by the second half of the backswing.*

Trail knee: *Remains more extended through the entire backswing (B), with slight abduction (varus) (A) and increasing internal rotation. The abduction moment decreases during this portion of the swing.*

End of the backswing in the frontal plane (C) and sagittal plane (D):

Lead knee: *Remains in an adducted position (C,D).*

Trail knee: *Reaches peak internal rotation (C,D).*

Downswing in the frontal plane (E) and sagittal plane (F):

Lead knee: *Quickly shifts into abduction (E). In the sagittal plane, the lead knee experiences maximum flexion at the beginning of the downswing (F), and then rapidly extends and internally rotates during the second half of the downswing. The knee experiences abduction and external rotation moments, at least during the initial portion of this swing phase.*

Trail knee: *In less flexion than the lead knee, and then rapidly extends and externally rotates beginning just after the lead knee (E,F). The peak extension moment occurs approximately halfway into the downswing, and the trail knee also sees abduction and external rotation moments.*

Ball-impact in the frontal plane (G) and sagittal plane (H):

Lead knee: *Remains in abduction (G) and begins to experience an adduction moment. The ACL faces maximal stress at ball-impact or just after.*

Trail knee: *Continues to experience abduction and external rotation moments.*

Follow-through in the frontal plane (I) and sagittal plane (J):

Lead knee: *Remains internally rotated, maintains a relatively constant abduction angle (I), and is in the least amount of flexion during this phase (J). The knee faces a minor extension moment, an internal rotation moment, and the peak adduction moment during this phase.*

Trail knee: *Remains externally rotated and is slightly more flexed than the lead knee (i). The knee faces an increasing flexion moment during the first part of the follow-through, while the abduction and external rotation moments decline toward the end of the stroke.*

knee in adduction during the downswing (Figure 1e), while Carson et al.[13] shows the trail knee to remain in abduction over the entire swing. Both knees experience increasing abduction moments during the first half of the downswing, with multiple studies showing peak abduction moments well before ball-impact.[13,18,20] In contrast, Purevsuren et al.[10] demonstrated a peak abduction moment in the lead knee at ball-impact or just after. The peak abduction moment for the lead knee was reported to be 0.70 Nm/Kg by Lynn et al.[20], 0.87 Nm/Kg +/- 0.25 Nm/Kg by Carson et al.[13], and 63.7 Nm +/- 24.5 Nm by Gatt et al.[18]. In the axial plane, both knees experience increasing external rotation moments during the first half of the downswing. By ball-impact, this changes to a small internal rotational moment in the lead knee.[13]

Follow-Through

During follow-through, both knees are in their least amount of flexion, and the trail knee has a slightly greater flexion angle (Figure 1i).[13,18,19] Murakami et al.[19] reported 16.5° +/- 9.4° and 19.1° +/- 6.5° of flexion at the end of the follow-through for the lead and trail knee, respectively. Similarly, Purevsuren et al.[10] found the lead knee to be in approximately 10° of flexion during this phase. After ball-impact, during the first half of the follow-through, an increasing flexion moment is seen by the trail knee, while a minor extension moment is seen by the lead knee. Although small, this was found to be the peak extension moment experienced by the lead knee during the entire swing and was reported as 0.51 Nm/Kg +/- 0.23 Nm/Kg by Carson et al.[13] In contrast, Gatt et al.[18] found this peak extension moment to occur before ball-impact, with a torque of 96.9 Nm +/- 29.0 Nm. Choi et al. [21] also concluded that the peak extension moment of the lead knee occurs during the downswing.

In the frontal plane, both knees also maintain a relatively constant abduction angle after ball-impact (Figure 1j).[10,13,18] The adduction moment seen in the lead knee at ball-impact remains relatively constant during the follow-through, while the abduction moment in the trail knee declines toward the end of the stroke.[13,20] The peak adduction moment in the lead knee is reported to be approximately 0.61 Nm/Kg +/- 0.40 Nm/Kg by Carson et al.[13] and 0.54 Nm/Kg by Lynn et al.[20], and is seen after ball-impact.

In the axial plane, the lead knee remains internally rotated and the trail knee stays in an externally rotated position. According to Purevsuren et al. [10], the maximal internal rotation angle for the lead knee is approximately 42.4°. The lead knee also experiences its peak internal rotation moment during the follow-through according to Carson et al.[13], while the external rotation moment noted in the trail knee at ball-impact decreases as the swing concludes. Conversely, multiple other studies have reported that the peak internal rotation moment to the lead knee occurs during the downswing.[10,18] Aside from the timing of this peak internal rotation moment, the magnitude has been reported to be to be 16.1 Nm, or 0.17 Nm/Kg +/- 0.09 Nm/Kg, depending on the units reported by each group of authors.[13,18] More studies including larger cohorts of golfers with different skill levels, genders, and club types may help to explain some of the differences between studies.

Lynn et al.[20] compared peak knee moments seen during the golf swing with those reported during other activities. As expected, peak knee adduction moments during the golf swing are higher than those seen during activities of daily living, including the normal gait cycle and stair climbing.[20] These increased adduction moments have been implicated in the progression of radiographic medial compartment osteoarthritis.[22] The peak abduction moment was found to be comparable to that observed with jump landing loads, but less than those described during sidestep cutting maneuvers.[20] It is also interesting that the peak abduction moment experienced by the lead knee is not affected by set-up position, but externally rotating the ipsilateral foot within a comfortable range reduced the peak adduction moment.[20] Hooker et al.[23] supported this finding, showing that the peak adduction moment in the lead knee was reduced with both external rotation of the lead foot and by having a wider stance without hinderance of swing speed. Lynn et al.[20] concluded that cumulative torque, such as that which may be experienced by regular golfers from thousands of swings over the course of many years, could compromise ligament integrity.

For the lead knee, the greatest overall force seen during the golf swing is compressive. According to Purevsuren et al.[10], this was found to occur during the follow-through phase, and was reported to be 375.7% body weight. In contrast, Gatt et al.[18] found both the peak compressive and anteriorly directed forces in the lead knee to occur during the downswing, with both knees facing peak anterior shear forces before ball-impact. Anterior/posterior and medial/lateral shear forces have both been demonstrated, and Purevsuren et al.[10] found these to be less than 100.0% body weight in the lead knee, with minimal changes occurring throughout the entire swing.

Effect on the ACL

To the authors' knowledge, the study by Purevsuren et al.[10] is the only one that specifically analyzed what forces the ACL experiences during the golf swing. This study evaluated the forces placed on the ACL of the lead limb in 10 professional golfers while hitting their driver.[10] Loading was found to be greatest during portions of the swing with smaller knee flexion, greater internal tibial rotation, greater knee abduction moments, and increased joint compressive forces.[10] Similarly, Markolf et al.[24] demonstrated in a cadaveric study that the combination of anterior tibial force and internal tibial torque near full extension presents the greatest risk for injury to the ACL. The combination of moments, joint angles, and forces resulting in the greatest force through the ACL was reported by Purevsuren et al.[10] to occur at ball-impact in three golfers and at the beginning of the follow-through in the remaining seven. The overall magnitude of force seen by the posterolateral (PL) bundle was greater than the anteromedial (AM) bundle. Specifically, the PL bundle experienced an average of 492.1 N +/- 246.8 N of force throughout the swing, versus 349.7 N +/- 194.9 N for the AM bundle.[10] These results are not surprising given the fact that the golf swing places mainly rotational forces through the knee. This is particularly evident by the high degree of internal tibial rotation and varus stress seen during follow-through.[10] The entire ligament was reported to face an average of 841.8 N +/- 437.1 N throughout the swing, with peak forces measured to be around 1,400 N.[10]

DISCUSSION

Throughout the golf swing, the lead and trail knees experience significant magnitudes of compressive and shear forces, and varying amounts of rotational torque around multiple axes. The lead knee generally faces greater loads, and physicians may therefore need to consider the laterality of injury when assessing return-to-play. The lead ACL is more stressed during times of smaller knee flexion, greater internal tibial rotation, and greater knee abduction moments, with the greatest load experienced around the time of ball impact.[10] Peak abduction forces experienced during the golf swing are comparable to those seen with a drop jump landing, and less than those seen with a pivot jump landing that mimics the side cutting maneuvers seen in sports like soccer and tennis.[20] Peak adduction moments are greater than those seen with walking and navigating stairs, but can be reduced by widening the stance and externally rotating the lead foot.[20,23]

In a study by Woo et al.[25], the ultimate load to failure of the native ACL was 2,106 N, but in age ranges 40 to 50 and 60 to 97. This significantly decreased to 1,503 N and 658 N, respectively. In professional golfers with an average age of 23.2, the ACL experiences an average of greater than 800 N throughout the swing, with peaks of around 1,400 N.[10] Purevsuren et al.[10] calculated that the maximum force seen by the ACL during the golf swing is between 38.8% to 48.7% of its ultimate tensile strength (UTS). The idea of fatigue failure to the ACL has therefore been postulated as a potential risk from the repetitive sub-maximal loading seen over many swings, but no direct evidence for this is known to have been published in the literature on this topic.[10,13]

A few emerging studies have started to investigate this concept of fatigue failure to the ACL. Chen et al.[26] studied tissue damage at the ACL's femoral enthesis in cadaveric adult knees that were repetitively loaded under 4 times-body weight pivot landing conditions, and found that this repetitive loading resulted in accumulation of tissue fatigue damage to the ACL's collagen fibril matrix. Given that approximately 75.0% of ACL failures are considered "non-contact," this study speaks to the possibility of cumulative damage factoring into these injuries.[26] Wojtys et al.[27] similarly concluded in cadaveric studies that "the human ACL can fail by a sudden rupture in response to repeated sub-maximal knee loading." They also discussed that the female ACL is more susceptible to fatigue failure because it is 21.0% to 34.0% smaller in cross sectional area, 17.0% to 27.0% smaller in volume, and consequently has a 22.0% lower tensile modulus of elasticity.[27] Granted that the golf-swing produces smaller knee loads than those seen with pivot landings, these studies are beginning to shine light on the overall concept of ACL fatigue failure in non-contact sports.

Given the ACL's role as a primary rotational stabilizer of the knee, the significant rotational forces generated by the golf swing may be especially important to consider after ACLR. In terms of postoperative rehabilitation and physical therapy, it is important to employ protocols that apply what is known about the repetitive stresses experienced by the ACL with each swing. For example, research may focus on determining if chipping and putting, which are expected to be lower in energy and torque than a driver or 5-iron, may be permitted to resume during an earlier phase of rehabilitation. Given the differences in size and direction of forces seen between trail and lead knee, the appropriate timing of return-to-play may also differ depending on the laterality of injury.

Depending on the type of fixation, the average initial graft fixation strength has been shown to range from around 382 N and 1,012 N in cadaveric studies.[28-31] Animal studies have reported graft incorporation to occur between 6 weeks and 12 weeks.[32-34] When bone plugs are employed, osseous healing is reported to occur between 6 weeks and 12 weeks, with tendon-to-bone healing taking place by 12 weeks.[32-34] A study by Unterhauser et al.[35] found maximal vascular density to the graft 6 weeks after ACL reconstruction in a sheep model, with vascularization levels most closely matching those of the native ACL after 24 weeks. Graft fixation strength maximizes once it is fully incorporated.

With peak loads faced by the ACL of up to around 1,400 N, golfers should be cautioned not to return to full swings before complete graft incorporation due to the risk of fixation failure.[10] Other factors also need to be considered, such as the time required to regain adequate strength to dynamic knee stabilizers to minimize the risk for reinjury, either to the ACL or another structure of the knee. A general consensus of the time frame for unrestricted exercises following ACLR is reported to be as early as 6 months, but high variability exists.[36] One study found patients who returned to knee-strenuous sport (soccer and team handball) before 9 months postoperatively incurred a 7-fold higher rate of ACL reinjury compared to the individuals who delayed return to sport until 9 months or later.[37] This is supported by another study showing patients who returned to pivot and contact sports 9 months or earlier had a 4.32-fold reinjury rate compared to those who returned after 9 months.[38] In their systematic review of ACL reconstruction protocols, Van Grinsven et al.[39] recommended that sport-specific agility training include turning and cutting maneuvers, which could be initiated between 16 weeks and 22 weeks postoperatively. Since golf is a non-contact sport with maximal ACL loads thought to be significantly less than those seen in pivoting sports, it may be reasonable to consider return to full participation closer to this time frame.

Return-to-play guidelines for golfers following TKA have already been proposed. At 4 weeks to 6 weeks, only putting is recommended, and at 6 weeks to 10 weeks, light chipping is permitted.[9] By 10 weeks to 12 weeks, half swing iron shots and drives are allowed to begin, and transition to full swings is suggested at 12 weeks to 14 weeks postoperatively.[9] Although generally agreed that return to the golf course is safe after TKA, these patients should be made aware that high repetitive loads through the knee may predispose the patient to polyethylene wear, and polyethylene patellar button failure.[3]

Other than the driver and 5-iron, little has been studied about how the knees are affected by the mechanics employed for use of other clubs. The majority of lies are non-uniform and rarely flat, and this variability may dramatically affect the cumulative forces experienced by both knees over the course of a whole round. In addition, many studies focused only on highly skilled golfers. Large cohort studies evaluating regular golfers of various skill levels would be needed to determine what knee injuries golfers are most at risk for, and biomechanical studies can help determine which structures see the most stress for the common shot types.

Knowledge of the forces that each knee experiences during the golf swing can be used to develop specific neuromuscular training regimens for injury prevention and safe return-to-play during recovery from ACLR. Such a program would employ exercises focused on strengthening muscles that help control rotational stability in both the axial and frontal planes. Maniar et al.[40] evaluated muscle activation in response to tibiofemoral shear forces, and valgus and rotational joint moments during a single leg drop landing in eight healthy males. The results demonstrated that the gluteus medius, gluteus minimus, and soleus muscles had the greatest potential to oppose the valgus joint moment; although these muscles do not cross the knee joint, they have secondary attachments via myofascial tissue to the gluteus maximum and iliotibial band which span the knee joint. It was also found that the internal rotation moment is opposed by the vastus intermedius, medialis, and lateralis in addition to the tibialis posterior, flexor digitorum longus, and flexor hallucis longer.[40] The hamstrings and soleus have been seen to be most responsible for resisting anterior tibial shear forces.[20] Future long-term studies would be required to determine which structures about the knee are most at risk for golf-related injury, and how effective proposed exercise routines may decrease injury rates.

Stress faced by other structures of the knee, including the menisci and collateral ligaments, have not been evaluated. The lateral collateral ligament (LCL) is known to play a role in limiting external rotation, particularly when the knee is in phases of extension, while the medial collateral ligament opposes abduction forces.[41] The mechanical effects and ability to play golf after partial meniscectomy or in the ACL-deficient state have also yet to be explored. These are areas where future research may add to the literature, providing evidence about which structures are most at risk, and improving understanding about injury prevention and rehabilitation strategies.

The golf swing produces several dynamic forces and moments to both knees, with the lead knee generally facing higher loads. The resulting stress transmitted to the lead ACL has been demonstrated to be moderately high, while the effect on other structures about the knee remains an area for future investigation. This repetitive stress may place the ACL at risk for attritional failure, and risk injury after ALCR. Return-to-golf after ACLR should therefore be gradual, and the biomechanical data summarized in this review may be used to help guide the development of appropriate postoperative rehabilitation protocols, and neuromuscular training programs for injury prevention.

REFERENCES

1. Baker ML, Epari DR, Lorenzetti S, et al. Risk factors for knee injury in golf: a systematic review. Sports Med. 2017;47(12):2621-2639. doi:10.1007/s40279-017-0780-5.
2. Mallon WJ, Callaghan JJ. Total knee arthroplasty in active golfers. J Arthroplasty. 1993;8(3):299-306. doi:10.1016/s0883-5403(06)80093-8.
3. Goldstein MJ, Ast MP, Dimaio FR. Acute posttraumatic catastrophic failure of a second-generation, highly cross-linked ultra-high-molecular-weight polyethylene patellar component. Orthopedics. 2012;35(7):e1119-e1121. doi:10.3928/01477447-20120621-35.
4. Gregori AC. Tibial stress fractures in two professional golfers. J Bone Joint Surg Br. 1994;76(1):157-158.
5. Guten GN. Knee injuries in golf. Clin Sports Med. 1996;15(1):111-128.
6. Hame SL, Kohler-Ekstrand C, Ghiselli G. Acute bucket-handle tear of the medial meniscus in a golfer. Arthroscopy. 2001;17(6):E25. doi:10.1053/jars.2001.21258.
7. Isaacs CL, Schreiber FC. Patellar osteochondral fracture: the unforeseen hazard of golf. Am J Sports Med. 1992;20(5):613-614. doi:10.1177/036354659202000522.

8. McCarroll JR. Fracture of the patella during a golf swing following reconstruction of the anterior cruciate ligament: a case report. Am J Sports Med. 1983;11(1):26-27. doi:10.1177/036354658301100107.
9. Papaliodis DN, Photopoulos CD, Mehran N, et al. Return to golfing activity after joint arthroplasty. Am J Sports Med. 2017;45(1):243-249. doi:10.1177/0363546516641917.
10. Purevsuren T, Kwon MS, Park WM, et al. Fatigue injury risk in anterior cruciate ligament of target side knee during golf swing. J Biomech. 2017;53:9-14. doi:10.1016/j.jbiomech.2016.12.007.
11. Jackson JD, Smith J, Shah JP, et al. Golf after total knee arthroplasty: do patients return to walking the course? Am J Sports Med. 2009;37(11):2201-2204. doi:10.1177/0363546509339009.
12. Rahnemai-Azar AA, Zlotnicki J, Burnham JM, et al. Secondary stabilizers of the anterior cruciate ligament—deficient knee. Operative Techniques in Orthopaedics. 2017;27(2):107-112. doi:10.1053/j.oto.2017.02.005
13. Carson H, Richards J, Coleman SGS. Could knee joint mechanics during the golf swing be contributing to chronic knee injuries in professional golfers? J Sports Sci. 2020;38(13):1575-1584. doi:10.1080/02640414.2020.1748956. PMID: 32252593
14. On the Mark: Get a swing trigger. PGATour. Accessed December 30, 2020. https://www.pgatour.com/tourreport/2012/05/on-the-mark-get-a-swing-trigger.html
15. Here's how Matthew Wolff created his unique pre-shot wiggle - Golf. Accessed January 10, 2021. https://golf.com/news/matthew-wolff-pre-shot-wiggle/
16. I just noticed a secret power move in Rory McIlroy's golf swing. Golf. Accessed January 10, 2021. https://golf.com/instruction/rory-mcilroy-golf-swing-power-move-video/
17. Severin AC, Tackett SA, Barnes CL, Mannen EM. Three-dimensional kinematics in healthy older adult males during golf swings. Sports Biomech. 2019:1-14. doi:10.1080/14763141.2019.1649452.
18. Gatt CJ, Pavol MJ, Parker RD, et al. Three-dimensional knee joint kinetics during a golf swing. Influences of skill level and footwear. Am J Sports Med. 1998;26(2):285-294. doi:10.1177/03635465980260022101.
19. Murakami K, Hamai S, Okazaki K, et al. In vivo kinematics of healthy male knees during squat and golf swing using image-matching techniques. The Knee. 2016;23(2):221-226. doi:10.1016/j.knee.2015.08.004.
20. Lynn SK, Noffal GJ. Frontal plane knee moments in golf: effect of target side foot position at address. J Sports Sci Med. 2010;9(2):275-281.
21. Choi A, Sim T, Mun JH. Quasi-stiffness of the knee joint in flexion and extension during the golf swing. Journal of Sports Sciences. 2015;33(16):1682-1691. doi:10.1080/02640414.2014.1003591.
22. Thorp LE, Sumner DR, Block JA, et al. Knee joint loading differs in individuals with mild compared with moderate medial knee osteoarthritis. Arthritis Rheum. 2006;54(12):3842-3849. doi:10.1002/art.22247.
23. Hooker QL, Shapiro R, Malone T, et al. Modifying stance alters the peak knee adduction moment during a golf swing. Int J Sports Phys Ther. 2018;13(4):588-594.
24. Markolf KL, Burchfield DM, Shapiro MM, et al. Combined knee loading states that generate high anterior cruciate ligament forces. J Orthop Res. 1995;13(6):930-935. doi:10.1002/jor.1100130618.
25. Woo SL, Debski RE, Withrow JD, et al. Biomechanics of knee ligaments. Am J Sports Med. 1999;27(4):533-543. doi:10.1177/03635465990270042301.
26. Chen J, Kim J, Shao W, et al. An anterior cruciate ligament failure mechanism. Am J Sports Med. 2019;47(9):2067-2076. doi:10.1177/0363546519854450.
27. Wojtys EM, Beaulieu ML, Ashton-Miller JA. New perspectives on ACL injury: on the role of repetitive sub-maximal knee loading in causing ACL fatigue failure. J Orthop Res. 2016;34(12):2059-2068. doi:10.1002/jor.23441.
28. Brown GA, Peña F, Grøntvedt T, et al. Fixation strength of interference screw fixation in bovine, young human, and elderly human cadaver knees: Influence of insertion torque, tunnel-bone block gap, and interference. Knee Surg, Sports traumatol, Arthroscopy. 1996;3(4):238-244. doi:10.1007/BF01466626.
29. Halewood C, Hirschmann MT, Newman S, et al. The fixation strength of a novel ACL soft-tissue graft fixation device compared with conventional interference screws: a biomechanical study in vitro. Knee Surg Sports Traumatol Arthrosc. 2011;19(4):559-567. doi:10.1007/s00167-010-1255-5.
30. Matthews LS, Lawrence SJ, Yahiro MA, et al. Fixation strengths of patellar tendon-bone grafts. Arthroscopy. 1993;9(1):76-81. doi:10.1016/s0749-8063(05)80348-2.
31. Smith PA, DeBerardino TM. Tibial fixation properties of a continuous-loop ACL Hamstring graft construct with suspensory fixation in porcine bone. J Knee Surg. 2015;28(6):506-512. doi:10.1055/s-0034-1394167.
32. Papageorgiou CD, Ma CB, Abramowitch SD, et al. A multidisciplinary study of the healing of an intraarticular anterior cruciate ligament graft in a goat model. Am J Sports Med. 2001;29(5):620-626. doi:10.1177/03635465010290051501.

33. Park MJ, Lee MC, Seong SC. A comparative study of the healing of tendon autograft and tendon-bone autograft using patellar tendon in rabbits. Int Orthop. 2001;25(1):35-39. doi:10.1007/s002640000199.
34. Tomita F, Yasuda K, Mikami S, et al. Comparisons of intraosseous graft healing between the doubled flexor tendon graft and the bone-patellar tendon-bone graft in anterior cruciate ligament reconstruction. Arthroscopy. 2001;17(5):461-476. doi:10.1053/jars.2001.24059.
35. Unterhauser FN, Bail HJ, Höher J, et al. Endoligamentous revascularization of an anterior cruciate ligament graft. Clin Orthop Relat Res. 2003;(414):276-288. doi:10.1097/01.blo.0000079442.64912.51.
36. Barber-Westin SD, Noyes FR. Factors used to determine return to unrestricted sports activities after anterior cruciate ligament reconstruction. Arthroscopy. 2011;27(12):1697-1705. doi:10.1016/j.arthro.2011.09.009.
37. Beischer S, Gustavsson L, Senorski EH, et al. Young athletes who return to sport before 9 months after anterior cruciate ligament reconstruction have a rate of new injury 7 times that of those who delay return. J Orthop Sports Phys Ther. 2020;50(2):83-90. doi:10.2519/jospt.2020.9071.
38. Grindem H, Snyder-Mackler L, Moksnes H, et al. Simple decision rules can reduce reinjury risk by 84% after ACL reconstruction: the Delaware-Oslo ACL cohort study. Br J Sports Med. 2016;50(13):804-808. doi:10.1136/bjsports-2016-096031.
39. van Grinsven S, van Cingel REH, Holla CJM, et al. Evidence-based rehabilitation following anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2010;18(8):1128-1144. doi:10.1007/s00167-009-1027-2.
40. Maniar N, Schache AG, Pizzolato C, et al. Muscle contributions to tibiofemoral shear forces and valgus and rotational joint moments during single leg drop landing. Scandinavian Journal of Medicine & Science in Sports. 2020;30(9):1664-1674. doi:10.1111/sms.13711.
41. Marshall RN, McNair PJ. Biomechanical risk factors and mechanisms of knee injury in golfers. Sports Biomechanics. 2013;12(3):221-230. doi:10.1080/14763141.2013.767371.