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Carson, H.J, Richards, James ORCID: 0000-0002-4004-3115 and Coleman, S.G.S (2020) Could knee joint mechanics during the golf swing be contributing to chronic knee injuries in professional golfers? Journal of Sports Sciences, 38 (13). pp. 1575-1584. ISSN 0264-0414

It is advisable to refer to the publisher's version if you intend to cite from the work.
<http://dx.doi.org/10.1080/02640414.2020.1748956>

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Could knee joint mechanics during the golf swing be contributing to chronic knee injuries in professional golfers?

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Running title: Knee joint mechanics during the golf swing in professional golfers

Key words: golf, driver, kinematics, kinetics, lower limbs

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Abstract

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Full three-dimensional movements and external moments in golfers' knees and the possible involvement in injuries have not been evaluated using motion capture at high sample frequencies. This study measured joint angles and external moments around the three anatomical axes in both knees of ten professional golfers performing golf drives whilst standing on two force plates in a motion capture laboratory. Significant differences were found in the knee joint moments between the lead and trail limbs for the peak values and throughout all stages during the swing phase. A significantly higher net abduction moment impulse was seen in the trail limb compared with the lead limb (-0.518 vs. -0.135 Nms.kg⁻¹), indicating greater loading over the whole swing, which could contribute to knee lateral compartment or ACL injuries. A significant correlation ($r=-0.85$) between clubhead speed at ball contact and maximum joint moment was found, with the largest correlations being found for joint moments at the top of the backswing event and at the end of the follow through. Therefore, although knee moments can contribute to high clubhead speeds, the large moments and impulses suggest that they may also contribute to chronic knee injuries or exacerbate existing conditions.

44 **Introduction**

45 The golf swing is a complex sequence of three-dimensional movements with the aim of
46 producing the required clubhead velocities and orientations for a given shot. Key factors to
47 achieve this include the magnitude and timing of muscular forces and moments. Many
48 researchers have studied kinematic and kinetic aspects of the swing since the seminal scientific
49 work of the Golf Society of Great Britain (Cochran & Stobbs, 1968), with much attention
50 directed towards upper body and trunk/pelvis motion, but little on leg actions during the swing.
51 This is strange, considering that Cochran and Stobbs stated “make no mistake: *the legs and*
52 *hips are the ‘engine’ of the swing; the arms and hands are the transmission system*” (p. 81;
53 original emphasis). Throughout the swing, the legs are responsible for transferring ground
54 reaction forces and torques to the upper body and onwards to the club. During the backswing,
55 the legs stabilise the pelvis to allow the trunk and shoulders to rotate away from the target, and
56 the magnitude of this rotation has been shown to be positively related to clubhead speed at
57 impact (McLean & Andrisani, 1997). Geisler (2001) suggested that supination of the front foot
58 and “lateral rotation of the patella” (presumably tibial external rotation) initiate the downswing.
59 After impact the legs are then used to help slow the lower body during the follow through.
60 Knowing the size of the moments and movements within the joints of the lower limbs is
61 therefore very important in helping our understanding of how clubhead velocities are attained.
62 However, currently there have been few studies focussing on leg actions in golf.

63

64 It is also important to consider how moments and movements of the lower limb joints could
65 contribute to injuries (Marshall & McNair, 2013). A recent systematic review reported that 3–
66 18% of golfing injuries occurred at the knee, however the reviewed studies gave little
67 information on the exact nature of the injuries or which knee was affected (Baker et al., 2017).
68 Baker et al. stated that although golf is considered a ‘low-impact’ sport, the prevalence of knee

69 injuries was comparable to high-impact sports such as basketball. They also identified knee
70 loading as a key factor in establishing knee injury risk mechanisms. Therefore, this aspect of
71 the swing needs further investigation.

72

73 Empirically, Gatt, Pavol, Parker and Grabiner (1998) were the first to examine knee kinematics
74 and kinetics during the golf swing and found that in the lead knee, the left knee in right-handed
75 golfers, the peak moments were 20.8 Nm and 96.9 Nm (flexion/extension), 16.1 Nm and 27.7
76 Nm (internal/external rotation) and 63.7 Nm and 24.4 Nm (abduction/adduction). The
77 respective values for the trail knee, the right knee in right-handed golfers, were 68.4 Nm, 58.6
78 Nm (flexion, extension), 19.6 Nm, 19.1 Nm (internal/external rotations) and 38.8 Nm, 52.6
79 Nm (abduction/adduction). The authors concluded that while these values were not high
80 enough for golf to be considered an activity with a high risk of traumatic knee injury for healthy
81 individuals, they could be of concern for those rehabilitating after ACL reconstruction or with
82 other knee pathologies. Lynn and Noffal (2010) measured external abduction and adduction
83 moments in the lead knee with the lead foot in a 'square' (neutral) position and with 30° of
84 external rotation. Mean peak external adduction moments were 0.63 and 0.54 Nm.kg⁻¹, and
85 abduction peak moments were 0.70 and 0.80 Nm.kg⁻¹ for the neutral and the externally rotated
86 foot positions respectively. The authors pointed out that these values were higher than those
87 for gait, stair climbing and drop jump landings but lower than those for side-cutting
88 manoeuvres. They concluded that using an externally rotated lead foot position could possibly
89 slow cartilage wear in healthy individuals and decrease pain in those with medial knee
90 pathology. More recently, Choi, Sim and Mun (2015) studied knee flexion and extension
91 kinetics and kinematics during drives of skilled and unskilled golfers. They found peak
92 extension moments of approximately 0.5–0.7 Nm.kg⁻¹ in the lead leg during the downswing in
93 the skilled golfers but clear extension peaks were not evident in the lead leg data of the

94 unskilled group. Although there are no definitive magnitudes for injury-causing moments in
95 golf, the values obtained were higher than those of 0.46 N.m.kg^{-1} for gait (Meireles, De Groot,
96 Van Rossoma, Verschueren, & Jonkers, 2017).

97

98 Thorp et al. (2006) noted that a single peak external moment only reflects the load on a joint at
99 a single time point, however this does not account for the combined load throughout the
100 duration of the movement. During gait, individuals ambulate at different speeds, therefore a
101 variable which incorporates both knee moment and the duration of the movement is needed.
102 Thorp et al. therefore calculated knee adduction angular impulse to enable the understanding
103 of knee loading over the whole stance phase of gait and its relationship to medial OA and found
104 higher values (0.20 vs. $0.11 \text{ N.m.s.kg}^{-1}$) in patients with moderate OA than healthy
105 participants. As the duration of the golf swing is different between individuals, knee
106 adduction/abduction angular impulse could also be valuable to quantify knee loading in golf.
107 This would allow a further exploration of the peak knee abduction moments which were found
108 to be greater than peak adduction moments in golf by Lynn and Noffal (2010). Similarly,
109 Devita, Hunter and Skelly (1992) used extension angular impulses to assess the effects of knee
110 braces on ACL-deficient patients, and so the present study will assess angular impulses in all
111 directions (extension/flexion, adduction/abduction and internal/external rotation).

112

113 Notably, there have been a number of methodological issues with previous biomechanics
114 research investigating joint moments during the golf swing. Firstly, several studies have used
115 low sample rates of 60–100 Hz for kinematic data collection. This, combined with low filter
116 cut-off frequencies, could lead to underestimation of peak values, particularly in the higher
117 derivatives used to calculate kinetic data in a fast action such as the golf swing. Secondly, three
118 studies utilised marker sets which do not allow six degrees of freedom analysis and may cause

119 errors in kinematic and kinetic data or miss important axes of motion (Richards, 2018). Thirdly,
120 only one paper allowed participants to use cleated golf shoes, whereas others used golfers in
121 regular athletic shoes or did not state the shoes used. Worsfold, Smith and Dyson (2008) have
122 shown that there are differences in ground reaction torques between cleated and flat-soled shoes
123 and thus this factor could have an important effect on knee moments.

124

125 Within the limited number of studies conducted in this area, none have measured three-
126 dimensional knee kinematics and kinetics in highly skilled golfers driving the ball when
127 wearing cleated shoes. Therefore, the purpose of this study was to quantify three-dimensional
128 knee joint kinetics and kinematics in the drives of professional golfers and, to examine how
129 external knee moments were related to clubhead speed. Furthermore, the differences in external
130 moments and impulses between lead and trail knees were compared to help identify which limb
131 was more at risk of possible injuries.

132

133 **Methods**

134 *Participants*

135

136 Ten right-handed male golfers ($M_{\text{age}} = 32.0 \pm 9.3$ years, $M_{\text{body mass}} = 79.03 \pm 11.12$ kg)
137 volunteered to take part. All participants were PGA professionals, which means that they do
138 not have current handicaps, but would have had to have handicaps of ≤ 4 to gain professional
139 status. The current handicap upper limit for CONGU Category 1 golfers is 5.4 (CONGU,
140 2018), indicating that the golfers in the present study can be classed as highly skilled. Ethical
141 approval was gained from the University's Ethics Committee, and prior to participation golfers
142 signed a consent form after reading an information sheet. All participants were free from
143 musculoskeletal injuries at the time of testing.

144

145 *Data Collection*

146

147 Retro-reflective markers (10 mm diameter) were attached by the same experimenter to each
148 golfer's body. The lower limbs were marked by attaching the markers on right and left sides at
149 the following anatomical landmarks; greater trochanter, medial and lateral femoral condyles,
150 medial and lateral malleoli, 1st and 5th metatarsal heads, calcaneus and the dorsal surface of the
151 foot. Rigid clusters consisting of four markers were also attached to the lateral surfaces of the
152 thigh and shank segments, approximately halfway between their proximal and distal
153 landmarks. Seven retro-reflective markers (6 mm) were attached to the head of the golf club;
154 four on the clubface and three on the crown (top) of the head. A ball was also marked with
155 retro-reflective tape. A cross of four markers was placed on the ground to aid with alignment
156 and provide reference directions (Figure 1). In addition, a marker was placed on the dorsal
157 surface of the left hand to enable the end of the swing to be identified.

158

159 ***Figure 1 here***

160

161 All golfers wore their own golf shoes and shorts. Participants carried out individualised warm-
162 ups consisting of stretches and practice tee shots. A static calibration trial for 1 s was collected
163 with the golfer in the anatomical standing position. They then performed eight drives with their
164 own drivers aiming to hit a marked squash ball to a vertical target placed 15 m away. Any
165 drives which the golfers were unhappy with were repeated.

166

167 *Equipment*

168

169 Participants performed shots whilst standing on artificial turf, which was attached with two-
170 sided tape to the top of two Force Plates (AMTI BP400600, AMTI, USA), ensuring that the
171 golfers had one foot on each plate. Ground reaction force data were sampled at 300 Hz. The
172 retro-reflective markers were tracked using a 10 camera Qualisys Oqus 700 system (Qualisys
173 Medical AB, Sweden) running at 300 Hz, which was synchronised with the force plates. Each
174 corner of both force plates were located in the motion capture coordinate system using
175 reflective markers which were then removed before golf testing. This calibration was repeated
176 before every testing session. The laboratory global coordinate system is shown in Figure 1.

177

178 *Data processing*

179

180 Four swing events were identified: Takeaway (TA; defined as when clubhead linear speed
181 crossed a threshold value of 0.0 ms^{-1}); Top of Backswing (TBS; defined when the club linear
182 velocity in the global z direction reached its lowest negative value); Ball Contact (BC; defined
183 as the frame immediately prior to the ball recording a positive linear speed) and Finish (FIN;
184 defined as when the left hand linear velocity in the global x -axis crossed a threshold of 0.0 ms^{-1}
185 after impact). These events were defined in the same way as reported by Carson, Richards and
186 Mazuquin (2019). Three swing phases were delineated by these four events: Backswing (TA
187 to TBS), Downswing (TBS to BC) and Follow through (BC to FIN). This is fewer phases than
188 other studies (e.g., Ball & Best, 2007), but it has been noted in other activities, such as counter-
189 movement jumps, that having more events does not necessarily better predict performance
190 (Moudy, Richter & Strike, 2018). Therefore, three phases were chosen for simplicity and
191 relevance for golf coaches and players.

192

193 Due to problems in viewing markers, not all trials were successfully tracked for all golfers. At
194 least five trials were available for each golfer, so raw kinematic and kinetic data for all
195 successfully-tracked trials (i.e., between five and eight) per participant were exported as c3d
196 files into Visual 3D v6.01.03 software (C-Motion Inc., USA). Kinematic and force plate data
197 were filtered using Generalised Cross Validated Quintic Splines (Woltring, 1985), which has
198 been shown to be a valid and objective method of smoothing sporting movement (Challis &
199 Kerwin, 1988, Giakas & Baltzopoulos, 1997). Knee joint angles were calculated using an X-
200 Y-Z Cardan sequence (flexion/extension [X], abduction/adduction [Y], internal/external
201 rotation [Z]). External knee moments were also calculated in Visual 3D with the shank as the
202 reference segment and were normalised to the participant's body mass (Lynn & Noffal, 2010;
203 Baker et al., 2017). Positive joint angles around the X, Y and Z axes represented flexion,
204 abduction and external rotation of both knees. Positive moments around X, Y and Z were
205 extension, adduction and internal rotation for both knees (Lynn & Noffal, 2010). External knee
206 angular moment impulses were calculated by the separate integration of the positive and
207 negative X, Y and Z components of the joint moments over the whole swing. Net angular
208 moment impulses in each direction were the computed by adding the negative and positive
209 impulses.

210

211 Kinematic and kinetic data were time-shifted so that BC was coincident at time = 0.0 s for all
212 golfers. Data were not normalised or event warped, as these manipulations affect higher
213 derivatives and often obscure the clarity of time series graphs. Peak knee moments around each
214 axis were identified from the data, including which phase they were in, and moments at the
215 four swing events were also identified.

216

217 *Statistical analysis*

218 Knee moments at the four swing events (TA, TBS, BC, FIN) and maximum and minimum
219 values were compared between the lead and trail limbs. Data were checked for normality with
220 Shapiro-Wilk tests with an α -level of 0.05, and if found to be normally distributed, left and
221 right data were compared using dependent t -tests with a Bonferroni-adjusted α -level of 0.003
222 (calculated as 0.05/18 tests). If data were found to be not normally distributed a Wilcoxon
223 Matched Pairs Signed Ranks test was carried out. Effect sizes were classified by Cohen's d
224 (Cohen, 1992) and 95% confidence limits were calculated for each comparison.

225

226 Knee angular impulses for the lead and trail legs were tested for normality and then compared
227 using dependent t -tests with a Bonferroni-adjusted α -level of 0.006 (0.05/9 tests) or a Wilcoxon
228 Matched Pairs Signed Ranks if not normally distributed, and effect sizes were classified by
229 Cohen's d (Cohen, 1992).

230

231 Clubhead speed at BC was correlated with knee joint moments at TBS, BC, FIN and peak
232 values using Pearson Product Moment Correlations with a Bonferroni-adjusted α -level of
233 0.003. For data that was not normally distributed a Spearman Rank Order correlation was
234 carried out. Correlation effect sizes were categorised by the reference values for correlations
235 (0.1 small; 0.3 moderate; 0.5 large; 0.7 very large; 0.9 nearly perfect) given by Hopkins,
236 Marshall, Batterham and Funin (2009).

237

238 **Results**

239

240 The mean (\pm SD) duration of the three phases (Backswing, Downswing and Follow through)
241 were 0.864 ± 0.134 s, 0.265 ± 0.043 s and 0.433 ± 0.044 s respectively. Intra-individual
242 variation in phase durations was lower than that between participants, particularly in the

243 downswing where each golfer was very consistent with a mean within-participant coefficient
244 of variation of only 2.2%. The mean clubhead speeds at BC were $42.09 \pm 3.15 \text{ m.s}^{-1}$ with a
245 range of 34.8–47.1 m.s^{-1} .

246

247 Figures 2a–2c show the three-dimensional knee joint angles for the lead and trail limbs. The
248 solid vertical line crossing the abscissa at time = 0.0 represents BC synchronised for all
249 participants and the dotted vertical line represents the mean value for all golfers' TBS. During
250 the backswing, participants displayed knee flexion, adduction and external rotation in the lead
251 limb, with slight knee extension flexion, abduction and internal rotation in the trail limb.
252 Maximal excursions for knee abduction/adduction for the lead limb and external/internal
253 rotation for both limbs were reached at the end of the backswing (TBS). For the first half of
254 the downswing both knees continued to flex but then extended rapidly, with the knee of the
255 lead limb commencing extension just prior to that of the trail limb, although considerable inter-
256 individual variations in timing were seen. The knee of the trail limb also adducted slightly in
257 the first part of the downswing followed by slight abduction. The knee of the lead limb
258 abducted rapidly from TBS to BC after which it stayed at a fairly constant angle. The knee on
259 the lead limb internally rotated rapidly from TBS to BC, which was accompanied by knee
260 external rotation in the trail limb.

261

262 ***Figure 2 here***

263

264 Figures 3a–3c show that during the backswing, the knee on the lead limb experienced a flexion
265 moment whilst the knee on the trail limb showed an extension moment. These increased to
266 their peak values approximately halfway through the downswing, after which they decreased
267 to close to zero at BC. During the follow through a small extension moment was seen in the

268 knee on the lead limb, which was accompanied by a large knee flexion moment in the trail
269 limb. In the frontal plane, initially both knees experienced small knee abduction moments
270 which increased in the lead limb but decreased in the trail limb during the backswing. At TBS
271 the knee abduction moments increased on both the trail and lead limbs, but the latter then
272 rapidly changed to an adduction moment at BC. During follow through, the lead limb still
273 experienced a knee adduction moment, whereas the trail limb had a slowly decreasing knee
274 abduction moment. During the backswing, the lead limb experienced a knee external rotation
275 moment whereas the trail limb experienced a knee internal rotation moment. After TBS, both
276 knees experienced an external rotation moment, but whilst this was maintained until BC for
277 the trail limb, the lead limb changed to a small internal rotation moment at BC. After impact,
278 the lead limb continued to experience a knee internal rotation moment, with the trail limb
279 showing a slowly decreasing knee external rotation moment. Similar to the movement timing,
280 there were clear inter-individual differences in joint moments during the whole swing, as
281 exemplified by two participants in Figure 4.

282

283 ***Figures 3 and 4 here***

284

285 Table 1 shows the peak knee joint moments in each anatomical direction (extension/flexion,
286 adduction/abduction and internal/external rotation).

287

288 ***Table 1 here***

289

290 Differences in knee joint moments between lead and trail limbs at swing events and maximum
291 and minimum were all normally distributed apart from peak flexion. Therefore, a Wilcoxon
292 Matched Pairs Signed Rank test was performed for this comparison and dependent *t*-tests were

293 carried out for all other contrasts. Results from the statistical tests are in Table 2, these show
294 that ten lead versus trail limb knee moment differences were significant ($p < 0.003$). Of the
295 significant results, seven showed greater knee moments in the lead limb and three showed
296 greater knee moments in the trail limb.

297

298

Table 2 here

299

300 External knee angular impulses are shown in Table 3. Statistical comparisons showed that
301 adduction and internal rotation impulses were significantly higher in the lead than in the trail
302 knee with large effect sizes. The abduction magnitude (in the negative direction) was
303 significantly higher in the trail than in the lead knee, again with large effect size. There was a
304 net abduction impulse over the whole swing for both knees, with the trail leg being significantly
305 greater (in negative direction) than the lead leg. There was also an overall net external rotation
306 impulse for both knees, with the lead knee being significantly greater (in the negative direction)
307 than the trail knee.

308

309

Table 3 here

310

311 Correlations between clubhead speed at BC and knee joint moments at TBS, BC and FIN did
312 not produce any significant results: however large–very large effects sizes were found for the
313 relationships between clubhead speed and lead limb knee adduction/abduction moment at TBS
314 ($r = -0.68$), the lead limb knee internal/external rotation moment at TBS ($r = -0.69$), and the
315 trail limb knee internal/external rotation moment at FIN ($r = -0.68$). Correlations of peak joint
316 moments with clubhead speed at BC produced only one significant relationship; with lead limb
317 knee adduction/abduction peak moment ($r = -0.85$; $p = 0.002$; effect size very large–near

318 perfect), although lead limb knee extension/flexion peak moment showed a large–very large
319 effect size ($r = -0.67$).

320

321 **Discussion**

322

323 The authors believe this is the first paper to present three-dimensional knee joint kinematics
324 and kinetics in the full swings of professional golfers using six degrees of freedom methods
325 with motion capture at a high sample frequency. The utilisation of golfers' own drivers and
326 golf shoes also meant that this study had greater ecological validity than previous studies.

327

328 Knee flexion and extension kinematics of the lead and trail limbs in the swing were very similar
329 to those presented by Choi et al. (2015), but were larger than those presented in other studies
330 (Gatt et al., 1998; Somjarod, Tanawat & Weerawat, 2011). In the frontal plane, the present
331 study showed knee abduction in the lead limb during the downswing with the trail limb
332 showing slight knee adduction. Although the ranges of motion were comparable to those
333 reported by Gatt et al., there were consistent 'offsets' from their results. Finally, the knee joints
334 showed less external/internal rotation during the downswing than the values presented by Gatt
335 et al. but more than in the paper of Somjarod et al. Although the kinematic curves over the
336 whole swing were similar to the aforementioned studies, differences between the present study
337 and previous research was possibly due to the marker sets and models used. In addition, there
338 were considerable inter-individual differences in the motions of our golfers, a fact also noted
339 by Choi et al., and so individual consideration must be paramount when attempting to translate
340 these data to the applied setting (Ball & Best, 2012).

341

342 Sagittal plane external knee joint moments for the first half of the downswing showed flexion
343 for the lead limb and extension for the trail limb. The peak values shown in Table 1 were
344 slightly above those of Choi et al. (2015) who gave graphical results of approximately -1.00
345 Nm.kg^{-1} and 0.75 Nm.kg^{-1} respectively, and very similar to those of Gatt et al. (-1.26 Nm.kg^{-1}
346 and 0.76 Nm.kg^{-1}). During the second half of the downswing knee moments were reversed so
347 that at BC there was a slight knee extension moment for both limbs. In the follow through the
348 lead limb experienced a small knee extension moment, whereas in the trail limb a large knee
349 flexion moment was seen (-0.77 Nm.kg^{-1}).

350

351 There has been previous interest in frontal plane knee moments, as it has been suggested that
352 these might lead to acute or chronic knee injuries such as Anterior Cruciate Ligament (ACL)
353 damage and OA. The present study found very similar peak values in the lead limb to the results
354 of Lynn and Noffal (2010). Peak values for adduction moments ($M = 0.49 \text{ N.m.kg}^{-1}$) were
355 above those reported by Mareiles et al. (2017) for healthy and early OA patients (0.46 Nm.kg^{-1})
356 but not as high as those with established OA (0.57 Nm.kg^{-1}). Interestingly, the present study
357 showed that the trail limb experiences higher knee abduction and lower adduction peak
358 moments than that of the lead limb. The large abduction moment took place just prior to BC
359 (Figure 3) and, whilst the ground reaction forces on the trail limb were small at this time, their
360 direction produced a large moment arm resulting in a large abduction moment. Large abduction
361 moments can lead to ACL stress (Fukuda, Woo & Loh, 2003) and although this was
362 commented upon by Lynn and Noffal for the lead limb, the greater external abduction moment
363 in the trail limb appears to show a greater risk of ACL injury. This could also be exacerbated
364 by the extension moment present in the trail limb during the downswing. The abduction
365 moment magnitudes were much higher (0.78 Nm.kg^{-1} and 0.87 Nm.kg^{-1} in the lead and trail
366 knee respectively) than those in adduction, and well above those reported for established OA

367 in adduction. The possible injury risks associated with external abduction moments were
368 reinforced by the abduction moment impulses for both knees over the whole swing, with the
369 trail limb again showing higher values. High impulses ($> 0.20 \text{ N.m.s.kg}^{-1}$) due to adduction
370 have been shown to be linked to medial OA (Thorp et al., 2006), so the much higher abduction
371 magnitudes ($0.34 \text{ N.m.s.kg}^{-1}$ for lead and $0.55 \text{ N.m.s.kg}^{-1}$ for trail knees) in this study may be
372 linked to lateral compartment problems. Although lateral OA is much less common than medial
373 OA, with 10% lateral compartment versus 90% medial compartment (Scott, Nutton & Biant,
374 2013), there is little information available on the prevalence of these conditions in golfers. This
375 confirms the findings of Mündermann, Dyrby, D’Lima, Colwell and Andriacchi (2008), who
376 used an instrumented total knee replacement and found that the golf swing had 40% more
377 loading on the lateral compartment compared to the medial. Future research should aim to
378 assess moment values in golfers suffering from knee pain to better illuminate our understanding
379 and provide meaningful indicators of risk.

380

381 Knee joint moments in the transverse plane during the downswing showed external rotation
382 moments followed by internal rotation moments for both limbs, with the lead limb reaching
383 peak knee external rotation values earlier in the downswing. Both limbs experienced the same
384 peak values and these were similar to those of Gatt et al. (1998). In the follow through the lead
385 limb had an internal rotation moment indicating a possible strain on the lead limb ACL (Meyer
386 & Haut, 2008). The trail limb had an external rotation moment throughout the follow through.

387

388 The large–very large effect sizes for the relationships between clubhead speed at BC and the
389 knee abduction moment and external rotation moment on the lead limb at TBS can be linked
390 to the need to stabilise the pelvis in the backswing in order to generate a maximal differential
391 in shoulder–hip rotation, sometimes called the “X-Factor” (McLean & Andrisani, 1997). This

392 is also supported by the significant correlation between lead knee peak abduction moment (at
393 ~40% of the downswing) and clubhead speed at BC. The large–very large effect size for the
394 correlation between the knee external rotation moment in the trail limb at FIN and clubhead
395 speed at BC may relate to the moments needed to slow the clubhead and to maintain balance
396 at FIN.

397

398 There were several limitations of this research. Firstly, the use of a squash ball instead of a golf
399 ball was chosen due to safety reasons in the laboratory. Impact characteristics between the club
400 head and a squash ball are different to those with a golf ball and due to the smaller mass of the
401 squash ball the club head will have decelerated less at impact. This might have changed swing
402 biomechanics during the Follow through and thus joint moments at FIN may have been
403 different than if a golf ball had been used. Nevertheless, joint moments at the other swing
404 events are unlikely to be different because the golfers, when asked after the testing sessions,
405 all reported that they had performed their normal swings. Another limitation was the small
406 homogenous sample size affecting statistical power and possibly obscuring theoretical
407 correlations. However there was large variation in some of the dependent variables (e.g., joint
408 moments; Figure 4), showing that even between participants with similar characteristics there
409 may be important individual differences. This means that each golfer needs individual analysis
410 to ascertain key factors such as knee abduction moments and moment impulse, as injury risks
411 may be different with different swings. This has already been pointed out in other aspects of
412 golf research (Ball & Best, 2012) but also applies to knee kinetics and kinematics. It may also
413 mean that more sophisticated analysis techniques, such as Statistical Parametric Mapping may
414 reveal more than the differences found in the present study.

415

416 **Conclusions**

417 This study showed that golfers undergo knee joint external moments during the golf swing
418 which, while are not usually of sufficient magnitude to directly cause acute injuries, may
419 contribute to chronic knee injuries or be hazardous to those with pre-existing conditions.
420 Whereas previous studies have concentrated on the lead limb, this paper showed that the trail
421 limb also experiences influential moments and associated loads on key structures. The large
422 abduction moments and impulses suggest that load is placed particularly on the lateral
423 compartment of the knee and might also stress the ACL. The large–very large effect sizes for
424 correlations between external knee moments, particularly at TBS and early downswing, and
425 the significant correlation between lead knee abduction moment with clubhead speed at BC,
426 support the statement of Cochran and Stobbs (1968) that the legs are “the engine of the swing”.

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Figure Captions

Figure 1. Marker sets on lower limbs, golf clubhead and ground reference with lab coordinate system.

Figure 2. Flexion/extension (a), abduction/adduction (b) and external/internal rotation (c) angles of the lead (left) and trail (right) knee joints during the swing.

Figure 3. Extension/flexion (a), adduction/abduction (b) and internal/external (c) joint moments of the lead (left) and trail (right) knee joints during the swing.

Figure 4. Exemplars of inter-individual differences in knee moments and timing across extension/flexion (a), adduction/abduction (b) and internal/external (c).