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| Title | Coupling motion between rearfoot and hip and knee joints during walking and single-leg landing |
| Author(s) | Koshino, Yuta; Yamanaka, Masanori; Ezawa, Yuya; Okunuki, Takumi; Ishida, Tomoya; Samukawa, Mina; Tohyama, Harukazu |
| Citation | Journal of electromyography and kinesiology, 37, 75-83 https://doi.org/10.1016/j.jelekin.2017.09.004 |
| Issue Date | 2017-12 |
| Doc URL | http://hdl.handle.net/2115/72264 |
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| Type | article (author version) |
| File Information | J Electromyogr Kinesiolo_37_75-83.pdf |



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Coupling motion between rearfoot and hip and knee joints during walking and single-leg landing

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Key Words: kinetic chain; foot pronation; ankle kinematics; lower limb; cross correlation; hindfoot; vector coding technique

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1 **Abstract**

2 The objective of the current study was to investigate the kinematic relationships between the
3 rearfoot and hip/knee joint during walking and single-leg landing. Kinematics of the rearfoot
4 relative to the shank, knee and hip joints during walking and single-leg landing were analyzed
5 in 22 healthy university students. Kinematic relationships between two types of angular data
6 were assessed by zero-lag cross-correlation coefficients and coupling angles, and were
7 compared between joints and between tasks. During walking, rearfoot eversion/inversion and
8 external/internal rotation were strongly correlated with hip adduction/abduction ($R = 0.69$ and
9 $R = 0.84$), whereas correlations with knee kinematics were not strong ($R \leq 0.51$) and varied
10 between subjects. The correlations with hip adduction/abduction were stronger than those
11 with knee kinematics ($P < 0.001$). Most coefficients during single-leg landing were strong (R
12 ≥ 0.70), and greater than those during walking ($P < 0.001$). Coupling angles indicated that hip
13 motion relative to rearfoot motion was greater than knee motion relative to rearfoot motion
14 during both tasks ($P < 0.001$). Interventions to control rearfoot kinematics may affect hip
15 kinematics during dynamic tasks. The coupling motion between the rearfoot and hip/knee
16 joints, especially in the knee, should be considered individually.

1 **1. Introduction**

2 The kinematics of the foot and ankle affect proximal joints kinematics, such as hip
3 and knee joints, during both static and dynamic conditions (Khamis and Yizhar, 2007;
4 Resende et al., 2015; Tateuchi et al., 2011). This linkage between foot/ankle and the proximal
5 joints may contribute to musculoskeletal injuries in the lower limbs (Chuter et al., 2012). For
6 example, the pathology of patellofemoral pain syndrome (Barton et al., 2009) and medial
7 tibial stress syndrome (Viitasalo et al., 1983) are reported to be related to dynamic foot
8 function. In addition, knee valgus, which is a risk factor for anterior cruciate ligament injury,
9 has been partially attributed to excessive foot pronation (Joseph et al., 2008). Excessive foot
10 and ankle motion may be associated with a variety of sports injuries in the lower limbs.

11 The effects of foot and ankle kinematics on lower limb joint kinematics have been
12 investigated in a small number of studies. Induced hyperpronation of the foot by wedges was
13 found to result in increases in internal rotation of both the knee joint and the hip joint during
14 standing (Khamis and Yizhar, 2007), increased hip internal rotation during single-leg standing
15 (Tateuchi et al., 2011), and increased internal rotation of the hip joint, femur and shank, as
16 well as changes in the temporal pattern of knee internal rotation during walking (Resende et
17 al., 2015). However, these studies examined the effect of the hyperpronation of the foot
18 induced by wedges, which may be beyond the range of normal foot motion. In a previous
19 study that did not induce foot motion, rearfoot eversion was found to be synchronized with
20 hip internal rotation (Souza et al., 2010) and correlated with hip adduction and shank internal
21 rotation during the stance phase of walking (Barton et al., 2012). However, to our knowledge,
22 the effects of rearfoot kinematics on the kinematics of the hip and knee joints have only been
23 examined during walking, and have not been examined during sports-related tasks such as
24 jump-landing, which is involved in a variety of sports and is associated with musculoskeletal
25 injuries of the lower limbs (Doherty et al., 2016; van der Does et al. 2016). Thus, examining

26 coupling motion during a landing task could provide basic information for assessment of joint
27 kinematics and for prevention and rehabilitation of musculoskeletal injuries of the lower
28 limbs in clinical settings.

29 Lafortune et al. (1994) examined the effects of a 10° pronation wedge and a 10°
30 supination wedge on knee kinematics using bone-pins during walking. Their results revealed
31 only minor changes in the knee angular pattern, suggesting that foot kinematics had a weak
32 effect on knee joint kinematics during walking. Although the findings suggested that tibial
33 rotation induced by pronation/supination wedges was resolved at the hip joint rather than the
34 knee joint, hip joint kinematics were not measured in the previous study (Lafortune et al.,
35 1994). Importantly, it is currently unclear whether foot kinematics have a stronger association
36 with the hip or knee joint during dynamic tasks. It is important for clinicians to understand the
37 interrelationships within the lower limb kinematics to address malposition of the hip or knee
38 joint. The current study had three main aims: to investigate the kinematic relationships
39 between the rearfoot and the hip and knee joints during walking and single-leg landing, to
40 investigate whether the relationship between the rearfoot and hip joint differed from those
41 between the rearfoot and knee joint, and to compare those relationships between walking and
42 single-leg landing. We hypothesized that rearfoot kinematics would be associated with hip
43 joint kinematics, whereas rearfoot kinematics would not be associated with knee joint
44 kinematics during both tasks.

45

46 **2. Methods**

47 ***2.1. Subjects***

48 Twenty-two healthy university students participated in this study (11 males, 11
49 females, age: 21.9 (1.1) years old, height: 167.2 (8.4) cm, body weight: 57.4 (6.6) kg). A
50 priori power analysis in G*Power 3.1.7 was performed using the correlation coefficients

51 between rearfoot and hip joint motion in a previous study (Souza et al., 2010). As a result, at
52 least 22 subjects were required to achieve statistical power of 80% with an alpha level of 0.05
53 for the correlation analyses. All participants had no history of surgery or fracture in the lower
54 limbs, and had no musculoskeletal injuries within the past 6 months. Because the dominant
55 side (the side used for kicking a ball) was the right leg in all subjects, the right lower limbs
56 were tested and analyzed. The experiments were performed after gaining ethical committee
57 approval from the University Institutional Review Board. Informed consent was obtained
58 from all subjects.

59

60 ***2.2. Procedure***

61 Six high-speed digital cameras (Hawk cameras, Motion Analysis Corporation, Santa
62 Rosa, CA, USA) and a force plate (Type 9286, Kistler AG, Winterthur, Switzerland) were
63 time-synchronized and used for motion analysis during walking and single-leg landing.
64 Reflective markers were attached to the bilateral anterior superior iliac spine, sacral, lateral
65 thigh, and lateral and medial femoral epicondyles. Markers of the shank and foot were
66 attached to the tibial tuberosity, the head of the fibula, lateral and medial malleoli, Achilles'
67 tendon attachment, posterior surface of the calcaneus, peroneal tubercle, sustentaculum tali,
68 tuberosity of the navicular, base of the first, second and fifth metatarsal, head of the first,
69 second and fifth metatarsal, and head of the proximal phalanx of the hallux, based on the
70 Rizzoli multi-segment foot model (Figure 1) (Leardini et al., 2007). EvaRT 4.3.57 (Motion
71 Analysis Corporation) software was used to record the marker coordinates during each task,
72 sampled at 200 Hz for kinematic data and 1000 Hz for force data.

73 For the walking task, subjects walked at their natural speed. For single-leg landing,
74 subjects dropped from a 30-cm box from their left leg, and landed with the right leg on the
75 force plate. Subjects practiced up to 10 trials of each task before recording, and performed

76 three successful trials for each task. Trials in which the entire right foot landing on the force
77 plate, the left foot did not touch the force plate, and the subject did not lose balance during
78 testing were defined as successful trials.

79

80 ***2.3. Data collection and reduction***

81 Kinematic data were low-pass filtered using a 4th order Butterworth filter with a 6 Hz
82 cutoff frequency. Hip and knee joint angles were calculated using the traditional lower limb
83 model (Helen Hayes model), and the rearfoot angle was calculated using the Rizzoli
84 multi-segment foot model (Leardini et al., 2007) using Visual 3D software (C-Motion Inc.,
85 Germantown, MD, USA). The Rizzoli multi-segment foot model has five segments, as
86 follows: shank, rearfoot, midfoot, forefoot and hallux. In the current study, the rearfoot angle
87 with respect to the shank was calculated according to the joint coordinate system (Grood and
88 Suntay, 1983). The angle data were extracted from initial contact to toe off during walking
89 and from initial contact to maximum knee flexion during single-leg landing. The initial
90 contacts during the both tasks were defined as the time at which the vertical ground reaction
91 force first exceeded 10 N, while toe-off during walking was defined as the time at which force
92 first fell below 10 N after initial contact. Joint and segment angles were set to zero during a
93 static standing position with the hip joints in a neutral position in the frontal plane and the
94 toes facing straight forward. The adduction and internal rotation of the hip and knee joints
95 were represented as positive values, while eversion and external rotation of rearfoot relative to
96 shank were represented as positive values.

97 Cross-correlation analysis was used to assess kinematic coupling between the hip and
98 knee joints and the rearfoot during each task. Cross-correlation analysis can determine the
99 strength of the temporal relationship between two time-series angular data sets (Souza et al.,
100 2010; Pohl et al., 2007). A cross-correlation coefficient is high when the two curves of angular

101 data sets have similar timing and shape (Wren et al., 2006). Zero-lag normalized cross
 102 correlation was calculated in the current study, because this represents the strength of the
 103 relationship between two time-series angular data sets in real time, and the coefficient with
 104 time lags between rearfoot and hip joint angular data was no stronger than that with a zero
 105 time lag (Souza et al., 2010). Zero-lag normalized cross correlation analysis was performed
 106 based on an equation described in a previous report (Nelson-Wong et al., 2009) using Matlab
 107 (The MathWorks Inc, Natick, MA):

$$108 \quad R_{xy} = \frac{\frac{1}{N} \sum_{n=1}^N (x_n - \bar{x})(y_n - \bar{y})}{\frac{1}{N} \sqrt{\sum_{n=1}^N (x_n - \bar{x})^2 \sum_{n=1}^N (y_n - \bar{y})^2}}$$

109 where R_{xy} is the correlation coefficient of two time-series data x and y and N represent the
 110 number of data points. The coefficients between the following angular data during walking
 111 and single-leg landing were calculated for each motion trial of each subject: hip adduction
 112 (ADD)/abduction (ABD) and rearfoot eversion (EVE)/inversion (INV), hip ADD/ABD and
 113 rearfoot external rotation (ER)/internal rotation (ER), hip IR/ER and rearfoot EVE/INV, hip
 114 IR/ER and rearfoot ER/IR, knee ADD/ABD and rearfoot EVE/INV, knee ADD/ABD and
 115 rearfoot ER/IR, knee IR/ER and rearfoot EVE/INV, and knee IR/ER and rearfoot ER/IR
 116 (Table 1). Interpretations of the coefficients were as follows: very strong (0.80 to 1.00 or
 117 -0.80 to -1.00), strong (0.60 to 0.79 or -0.60 to -0.79), moderate (0.40 to 0.59 or -0.40 to
 118 -0.59), weak (0.20 to 0.39 or -0.20 to -0.39) and very weak (0 to 0.19 or 0 to -0.19)
 119 (Campbell and Swinscow, 2009).

120 Since the results of zero-lag normalized cross correlation analysis were not reflected
 121 by the magnitude of the time-series angular data, the analysis cannot assess the quantity of
 122 coupling motions. Therefore, a vector coding (coupling angle) technique was used to assess
 123 the quantity of kinematic couplings of interest, based on an equation described in a previous
 124 report (Pohl et al., 2007):

125 $\Theta_i = \text{abs}\left[\tan^{-1}\left(\frac{y_{i+1}-y_i}{x_{i+1}-x_i}\right)\right]$

126 where Θ_i is the coupling angle between proximal (x) and distal (y) joint angles, and i
127 represents the number of data points. The proximal joint motion is greater when the coupling
128 angle $< 45^\circ$, whereas the distal joint motion is greater when the coupling angle $> 45^\circ$. The
129 mean coupling angles were calculated for the period of interest.

130

131 **2.4. Statistical analysis**

132 Zero-lag normalized cross correlation coefficients and coupling angles of each
133 subject were set as the dependent variables. Shapiro-Wilk tests revealed that most coefficients
134 were not normally distributed, while all coupling angles other than that of rearfoot EVE/INV
135 and knee IR/ER were normally distributed. Thus, Wilcoxon signed-rank tests and paired
136 t-tests were used to investigate whether the strength of correlations and coupling angles
137 between the rearfoot and hip joint differed from the strength of correlations between the
138 rearfoot and the knee joint, respectively. The significance level was set at 0.0125 with a
139 Bonferroni correction based on the four comparisons: 1) rearfoot EVE/INV or ER/IR and hip
140 ADD/ABD vs. rearfoot EVE/INV or ER/IR and knee ADD/ABD; 2) rearfoot EVE/INV or
141 ER/IR and hip ADD/ABD vs. rearfoot EVE/INV or ER/IR and knee IR/ER; 3) rearfoot
142 EVE/INV or ER/IR and hip IR/ER vs. rearfoot EVE/INV or ER/IR and knee ADD/ABD; 4)
143 rearfoot EVE/INV or ER/IR and hip IR/ER vs. rearfoot EVE/INV or ER/IR and knee IR/ER
144 (Table 1). In addition, Wilcoxon signed-rank tests and paired t-tests were used to compare the
145 coefficients and coupling angles between walking and single-leg landing, respectively, and the
146 significance level was set at 0.0125 with a Bonferroni correction based on the four
147 comparisons of rearfoot EVE/INV and rearfoot ER/IR.

148

149 **3. Results**

150 **3.1. Walking**

151 Averaged time-series angular displacements of hip joint, knee joint, and rearfoot
152 relative to the shank during walking are shown in Figure 2. Rearfoot EVE/INV was strongly
153 correlated with hip ADD/ABD (median $R = 0.69$), and the correlation was significantly
154 stronger than the correlations between the rearfoot EVE/INV and knee ADD/ABD and that
155 between the rearfoot EVE/INV and knee IR/ER (all: $P < 0.001$; Table 2). Most subjects
156 exhibited greater than or equal to moderate correlations between rearfoot EVE/INV and hip
157 ADD/ABD (Figure 3). Rearfoot EVE/INV had weak correlations with hip IR/ER, knee
158 ADD/ABD and knee IR/ER (median $R = 0.06, 0.37$ and -0.04 , respectively) (Table 2). These
159 correlations varied considerably between subjects (Figure 3). Rearfoot ER/IR had a very
160 strong correlation with hip ADD/ABD (median $R = 0.84$), and the correlation was
161 significantly stronger than the correlation between rearfoot ER/IR and knee ADD/ABD, and
162 that between rearfoot ER/IR and knee IR/ER (all: $P < 0.001$; Table 2). Most subjects exhibited
163 greater than or equal to moderate correlations between rearfoot ER/IR and hip ADD/ABD
164 (Figure 3). Rearfoot ER/IR had weak to moderate correlations with hip IR/ER, knee
165 ADD/ABD and knee IR/ER (median $R = -0.26, R = 0.51$ and -0.41 , respectively) (Table 2),
166 and these correlations varied considerably between subjects (Figure 3).

167 The coupling angles between the rearfoot and hip joint were significantly smaller
168 than those between the rearfoot and knee joint during walking (all: $P < 0.001$; Table 3). This
169 result indicated that hip joint motion relative to rearfoot motion was greater than knee joint
170 motion relative to rearfoot motion. The mean coupling angles indicated slightly greater hip
171 ADD/ABD and IR/ER motion relative to rearfoot motion, and less knee ADD/ABD motion
172 and slightly less knee IR/ER motion relative to rearfoot motion (Table 3).

173

174 **3.2. Single-leg landing**

175 Averaged time-series angular displacements of the hip joint, knee joint, and rearfoot
176 relative to shank during single-leg landing are shown in Figure 4. Rearfoot EVE/INV had a
177 very strong correlation with hip IR/ER and knee IR/ER (median $R = 0.89$ and 0.87 ,
178 respectively) and a strong correlation with hip ADD/ABD and knee ADD/ABD (median $R =$
179 0.70 and 0.79 , respectively) (Table 4). However, some subjects exhibited a weak or negative
180 correlation (Figure 5). The correlations with rearfoot EVE/INV were not significantly
181 different between the hip and knee. Rearfoot ER/IR had a very strong correlation with hip
182 ADD/ABD, hip IR/ER and knee ADD/ABD (median $R = 0.92$, 0.92 and 0.80 , respectively),
183 and was strongly correlated with knee IR/ER (median $R = 0.79$) (Table 4). Although most
184 subjects exhibited greater than or equal to strong correlations between rearfoot ER/IR and hip
185 ADD/ABD or IR/ER, some subjects exhibited a weak or negative correlation between
186 rearfoot ER/IR and knee ADD/ABD or IR/ER (Figure 5). The correlation between rearfoot
187 ER/IR and hip ADD/ABD was significantly stronger than the correlation between rearfoot
188 ER/IR and knee IR/ER ($P = 0.001$) and was no different to the other correlations (Table 4).

189 The coupling angles between the rearfoot and hip joint were significantly less than
190 those between the rearfoot and knee joint (all: $P < 0.001$; Table 5). Therefore, hip joint motion
191 relative to rearfoot motion was greater than knee joint motion relative to rearfoot motion. The
192 mean coupling angles indicated slightly greater hip joint motion and slightly less knee joint
193 motion, relative to rearfoot motion (Table 5).

194

195 **3.3. Comparison between the tasks**

196 A comparison between the walking and single-leg landing conditions revealed that
197 the correlations between rearfoot EVE/INV and hip IR/ER, and those between rearfoot
198 EVE/INV and knee IR/ER were significantly stronger in the single-leg landing condition than
199 in the walking condition (both, $P < 0.001$). The correlations between rearfoot ER/IR and hip

200 ADD/ABD, between rearfoot ER/IR and hip IR/ER, and between rearfoot ER/IR and knee
201 IR/ER were also significantly stronger in the single-leg landing condition compared with the
202 walking condition (all, $P < 0.001$).

203 The coupling angles between rearfoot EVE/INV and hip IR/ER, between rearfoot
204 EVE/INV and knee ADD/ABD, and between rearfoot ER/IR and knee ADD/ABD were
205 significantly smaller in the single-leg landing condition compared with the walking condition
206 ($P = 0.001$, $P < 0.001$, and $P < 0.001$, respectively). This indicates that hip IR/ER and knee
207 ADD/ABD motion relative to rearfoot motion was greater in the single-leg landing than in the
208 walking condition.

209

210 **4. Discussion**

211 The current study revealed that rearfoot motion in the frontal and horizontal planes
212 was most strongly correlated with hip frontal plane motion during walking. However, other
213 correlations were not strong, and varied considerably between individuals during walking. In
214 the single-leg landing condition, all correlations between rearfoot and hip and knee joints
215 ranged from strong to very strong, and most correlations were significantly stronger than
216 those in the walking condition. In addition, although proximal joint motion relative to rearfoot
217 motion was greater in the hip joint than in the knee joint during both tasks, some of the
218 relative proximal joint motions were greater in single-leg landing than in walking. These
219 findings suggest that the strength of kinematic relationships and the relative amount of
220 coupling motion with rearfoot motion differed between the hip and knee joints, and was
221 task-dependent.

222 Rearfoot EVE/INV and ER/IR motion were the most strongly correlated with hip
223 ADD/ABD motion during walking. Rearfoot EVE and ER would be expected to cause
224 internal rotation of the shank and femur under closed-kinetic conditions (Khamis and Yizhar,

225 2007; Resende et al., 2015). Since the knee position is slightly flexed during most of the
226 stance phase of walking (Lafortune et al., 1992), shank and femur internal rotation may shift
227 the knee medially, resulting in hip adduction. The present findings are partially in accord with
228 those of a previous study by Barton et al. (2012), who reported that the range of motion in
229 rearfoot eversion was associated with the peak value and range of motion in hip adduction
230 kinematics during walking in healthy subjects and patellofemoral pain syndrome subjects.
231 However, this previous study assessed the kinematic relationship with Pearson's correlation
232 coefficients using discrete variables, and did not assess the relationship with temporal
233 kinematic patterns (Barton et al, 2012). In the present study, the kinematic patterns of the
234 rearfoot were synchronized with the pattern of hip ADD/ABD motion. The amount of hip
235 ADD/ABD motion was slightly greater relative to that of rearfoot motion in the coupling
236 motion, as indicated by the coupling angle. The present findings indicated that interventions
237 to control the motion pattern of rearfoot eversion and external rotation may affect hip
238 adduction motion patterns during walking, and vice versa.

239 The temporal kinematic relationships between the rearfoot and knee joint were found
240 to be relatively weak and varied considerably between subjects during walking in the present
241 study. The relative amount of coupling motion with the rearfoot was also less in the knee joint
242 than the hip joint. Lafortune et al. (1994) reported that foot inversion or eversion induced by
243 10° valgus or varus wedges caused minor changes in knee joint motion (less than 1°) during
244 walking. Foot pronation induced by 10° wedged sandal resulted in constant increase in the hip
245 internal rotation, but no constant increase in the knee internal rotation during walking
246 (Resende et al., 2015). In another study, foot posture (such as the planus and cavus foot types)
247 also had only minor effects on knee joint motion and moment during walking (Buldt et al.,
248 2015). The ligament and muscles at the knee joint may resist the kinematic chain through
249 shank motion induced by rearfoot motion during walking (Souza et al.. 2010; Lafortune et al.,

250 1994). Therefore, foot motion may not strongly affect knee motion during walking. However,
251 the kinematic relationships should be considered individually, because some subjects
252 exhibited a strong relationship (Figure 3).

253 In the current study, in the single-leg landing condition, rearfoot EVE/INV and
254 ER/IR motion had very strong or strong correlations with hip joint motion, as well as knee
255 joint motion. In addition, hip IR/ER and knee ADD/ABD motion relative to rearfoot motion
256 were greater in single-leg landing than in walking. A previous study found that changing foot
257 position during drop vertical jump significantly affected knee kinematics and kinetics in the
258 frontal and horizontal planes (Ishida et al., 2015). Rearfoot motion may have major effects on
259 knee and hip joint motion during the landing task. Single-leg landing may have resulted in
260 decreased compliance of the soft tissues via strong contraction of the muscles around the
261 ankle to attenuate landing impact (Yeow et al., 2011). Stiffness around the joint may result in
262 a strong correlation between the rearfoot and hip and knee kinematics, as Pohl et al. (2007)
263 speculated. In addition, the joint angular velocities in most joints of the lower limbs would be
264 expected to be high during single-leg landing (Dowling et al., 2012). Subjects may have had
265 difficulty controlling rapid joint motion with the muscles, meaning that rearfoot motion may
266 have been predisposed to link both the knee and hip joint during single-leg landing.

267 The results of the current study revealed considerable individual variation in some
268 coupling motions. A previous study investigating coupling motion between rearfoot EVE/INV
269 and hip IR/ER in the walking stance suggested that coupling strength should be considered
270 individually in clinical settings (Souza et al., 2010). The current study also suggests that the
271 coupling motion between rearfoot and hip IR/ER during walking should be considered
272 individually. Furthermore, the current findings suggest that the coupling motion between the
273 rearfoot and knee joint should also be considered individually during not only walking but
274 also single-leg landing. The variation in the coupling motion may be caused by multiple

275 factors, such as foot posture, lower limb alignment, joint laxity and muscle function. Future
276 studies are required to clarify the cause of this individual variation.

277 The present study involved several limitations that should be considered. First, the
278 coupling motion between the rearfoot and hip and knee joints in other tasks may differ from
279 the present findings because the characteristics of the coupling motion were task-dependent.
280 Future studies should investigate coupling motion during running, cutting maneuvers or
281 double-leg landing tasks. Second, we used cross-correlation analysis between two types of
282 angular data based on the assumption that they would be independent. In actuality, two
283 angular data types would not be expected to be completely independent because of
284 mechanical connections between joints. The coupling motion types observed in the present
285 study would include the mechanical coupling and conscious coupling. Finally, the present
286 study examined only healthy subjects. Subjects with musculoskeletal injury or surgery in the
287 lower limbs may exhibit different coupling motion patterns from the current findings.

288

289 **5. Conclusion**

290 The current study found that rearfoot EVE/INV and ER/IR motion were most
291 strongly correlated with hip ADD/ABD motion, while the correlations between the rearfoot
292 motion and knee joint motion were not strong and varied between individuals during walking.
293 In the single-leg landing condition, rearfoot EVE/INV and ER/IR motion were strongly
294 correlated with both hip and knee joint motion. The hip joint motion relative to rearfoot
295 motion was greater than the knee joint motion relative to rearfoot motion in the coupling
296 motion during both tasks. These findings suggest that the strength of kinematic relationships
297 and the relative amount of coupling motion with rearfoot motion differed between the hip and
298 knee joints, and that this effect was task-dependent.

299

300 **Acknowledgements**

301 We thank Benjamin Knight, MSc, from Edanz Group (www.edanzediting.com/ac)
302 for editing a draft of this manuscript.

303

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Figure captions

Figure 1. Marker location.

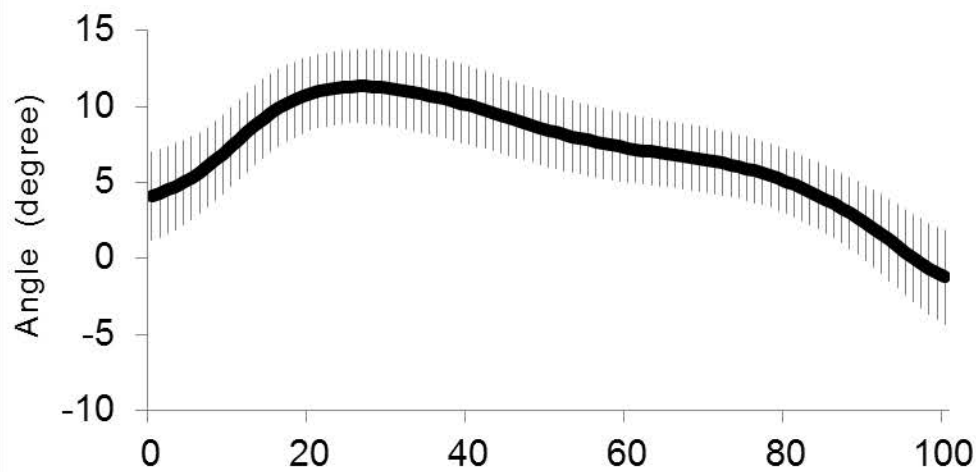
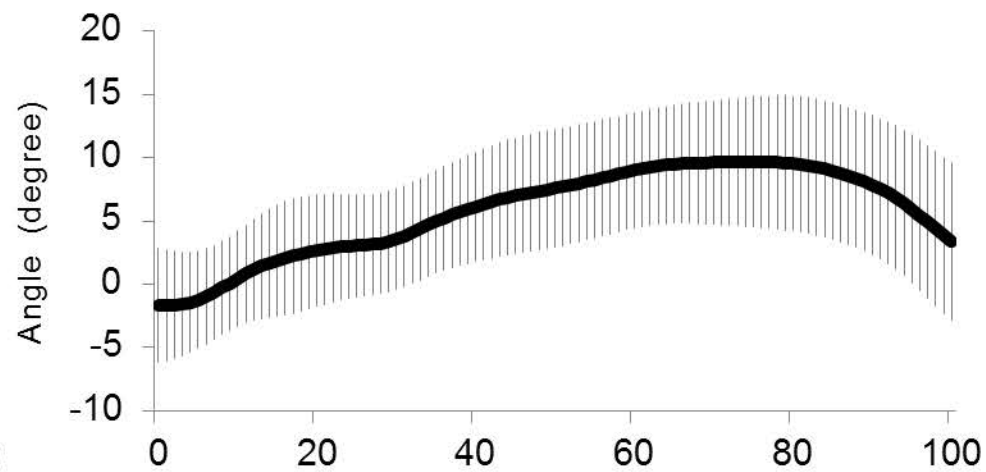
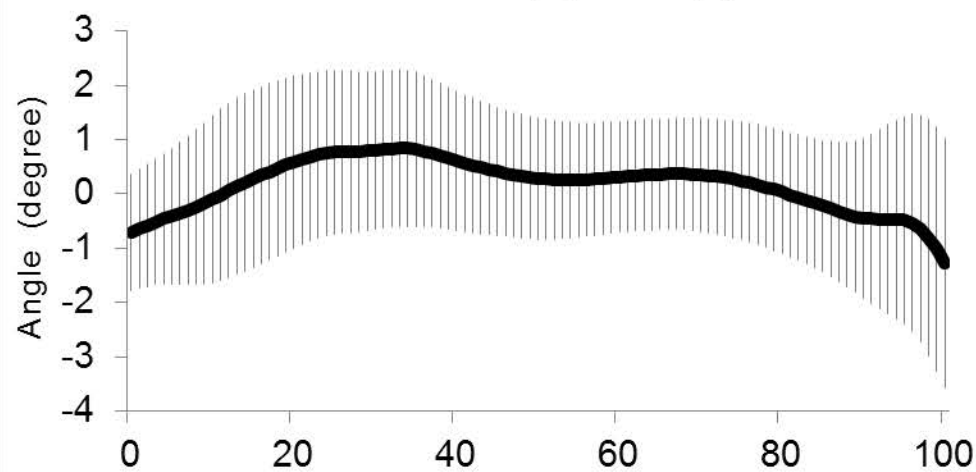
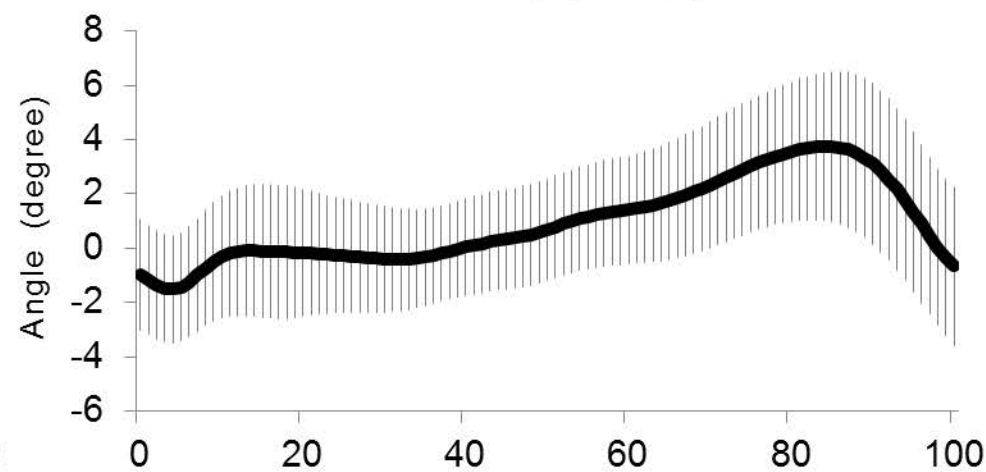
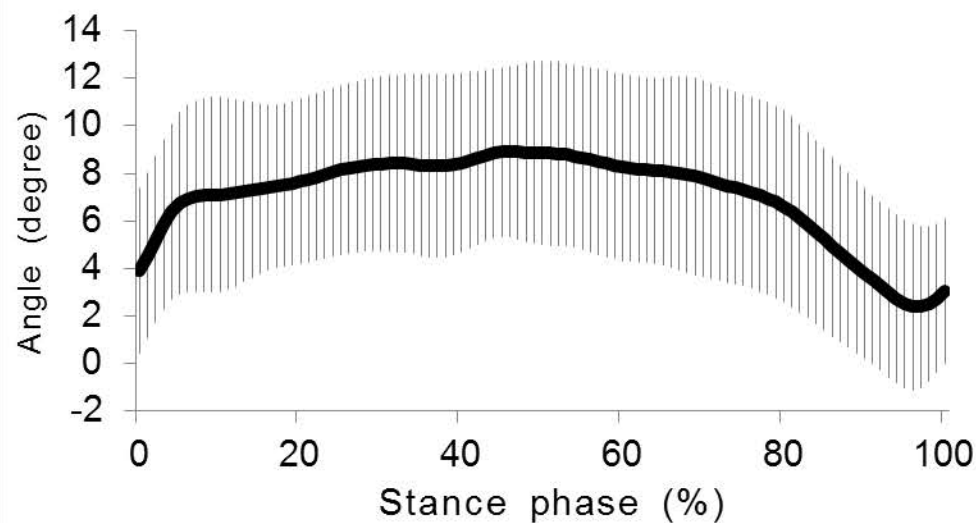
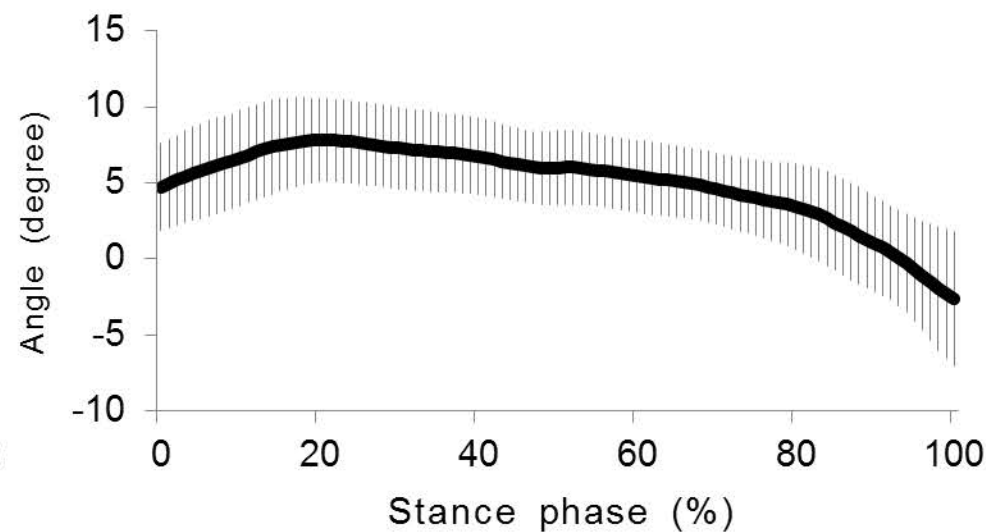
Figure 2. Averaged time-series angle data (mean \pm SD) during walking. The horizontal axis indicates the stance phase from initial contact (0%) to toe-off (100%).

Figure 3. Frequency diagram of the correlation coefficients between rearfoot motion and knee and hip motion during walking in 22 subjects. The vertical axis indicates the number of subjects. The horizontal axis indicates the correlation coefficient.

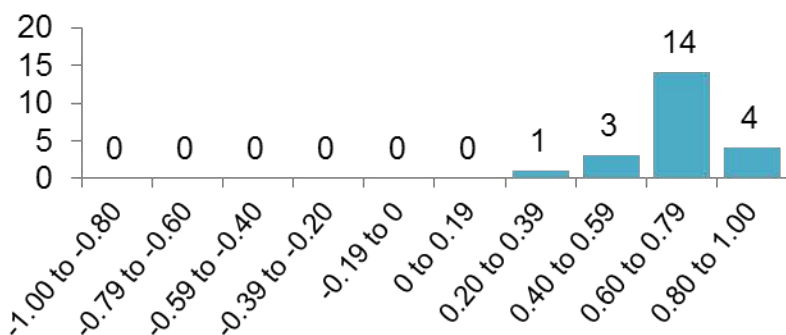
Figure 4. Averaged time-series angle data (mean \pm SD) during single-leg landing. The horizontal axis indicates the landing phase from initial contact (0%) to maximum knee flexion (100%).

Figure 5. Frequency diagram of the correlation coefficients between rearfoot motion and knee and hip motion during single-leg landing in 22 subjects. The vertical axis indicates the number of subjects. The horizontal axis indicates the correlation coefficient.

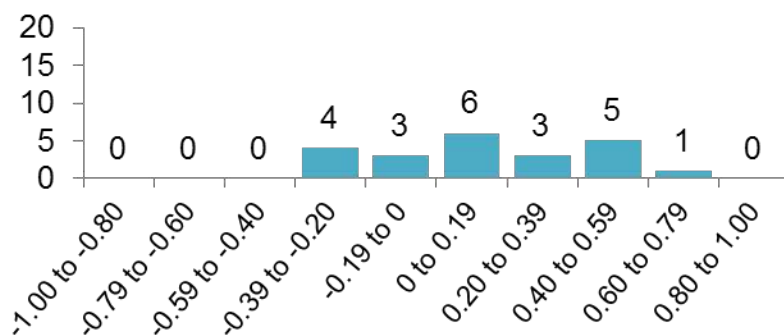


Hip ADD(+)/ABD(-)**Hip IR(+)/ER(-)****Knee ADD(+)/ABD(-)****Knee IR(+)/ER(-)****Rearfoot EVE(+)/INV(-)****Rearfoot ER(+)/IR(-)**

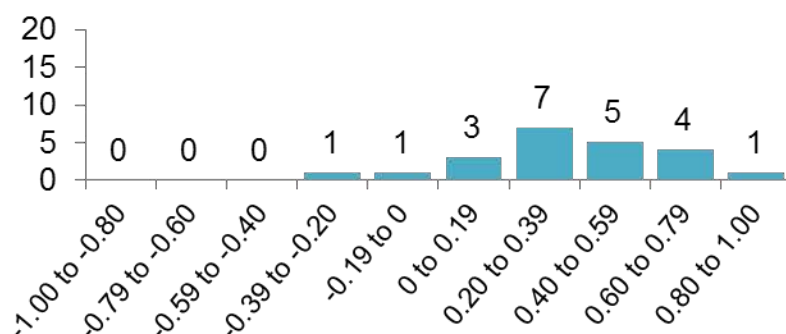
Correlation between rearfoot EVE/INV and hip ADD/ABD



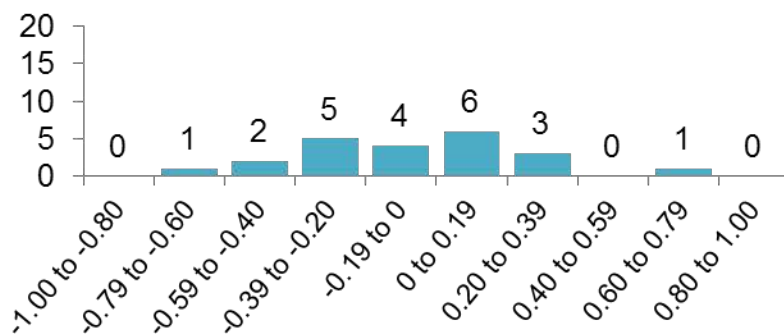
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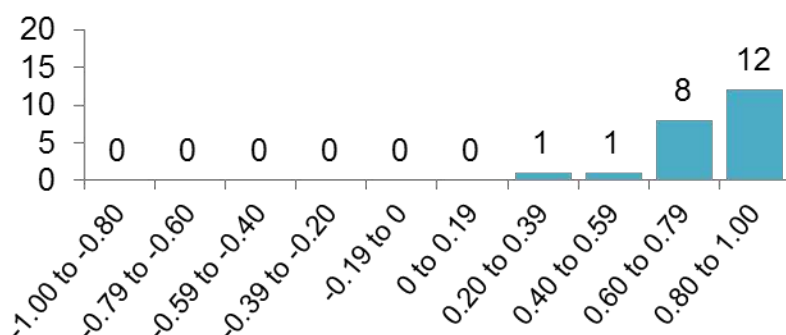
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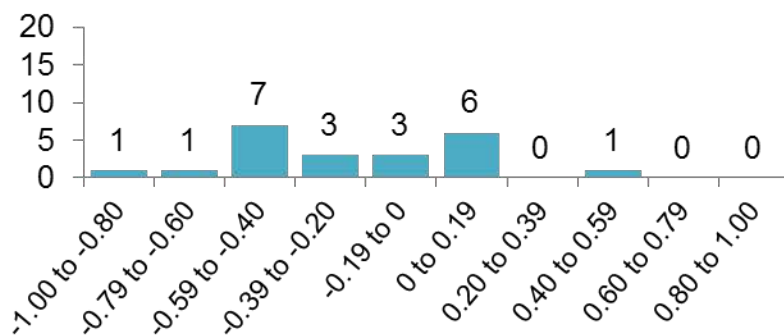
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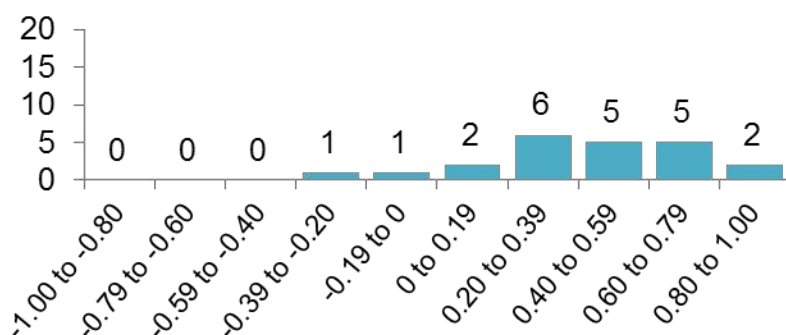
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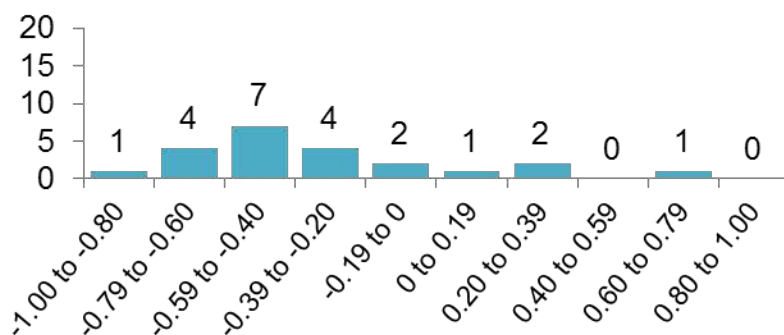
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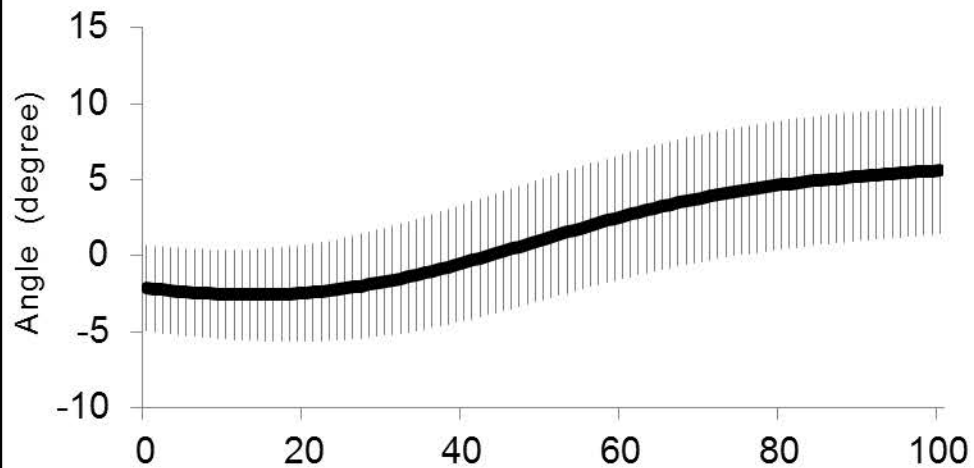
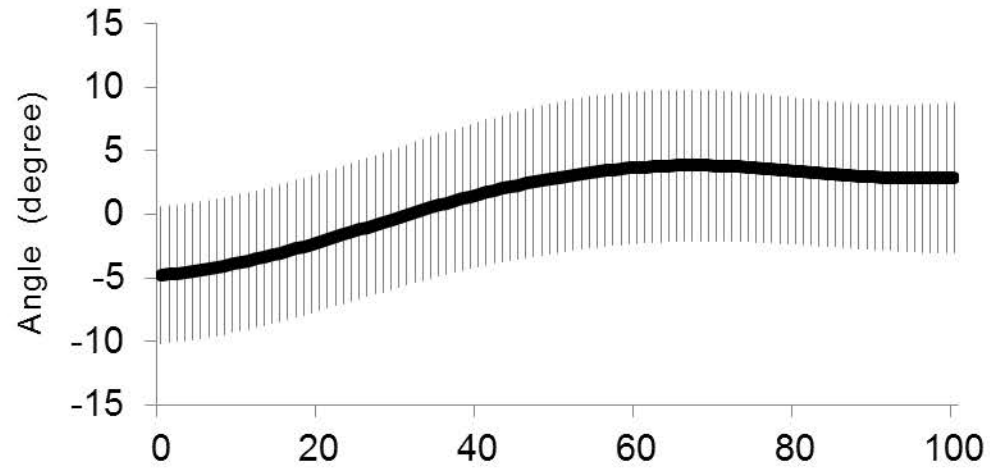
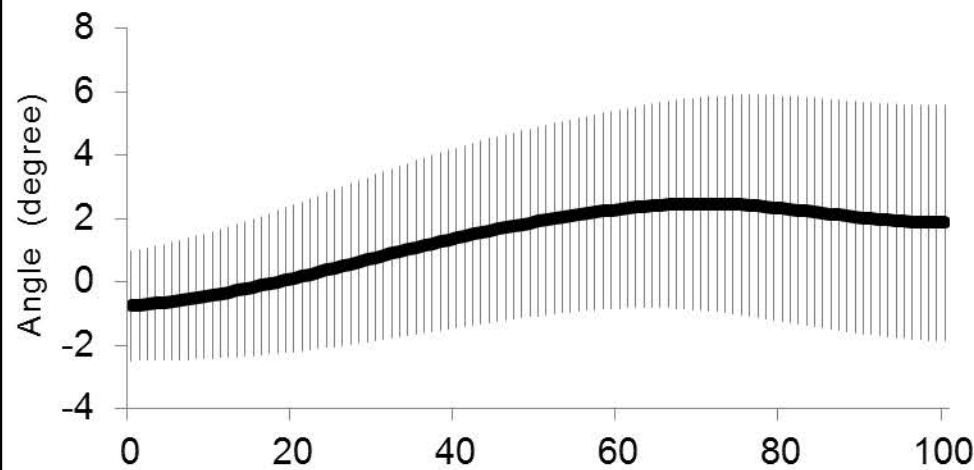
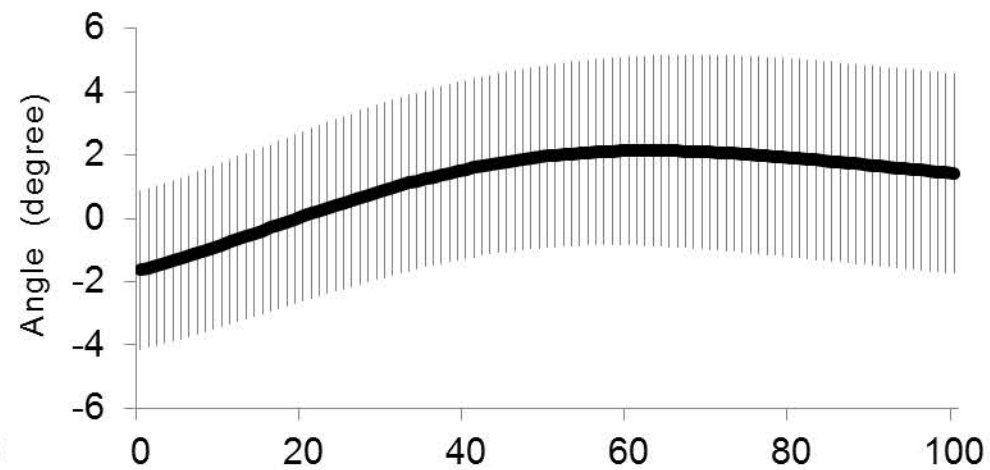
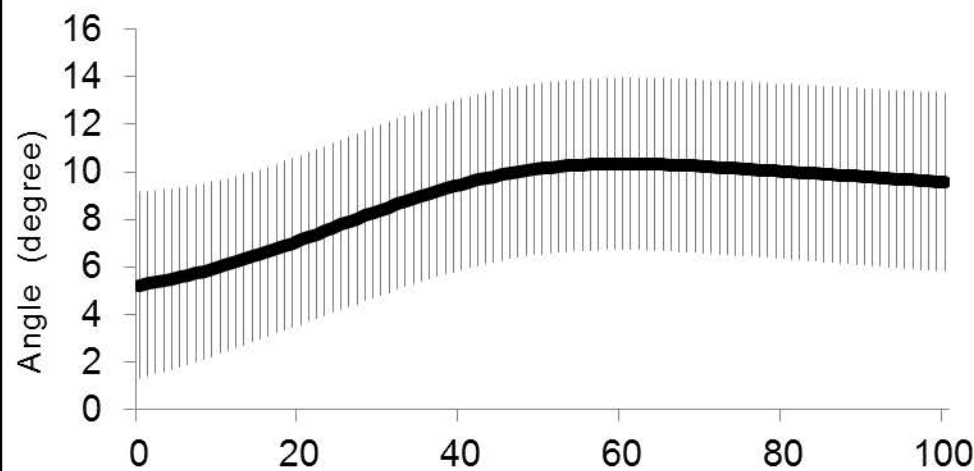
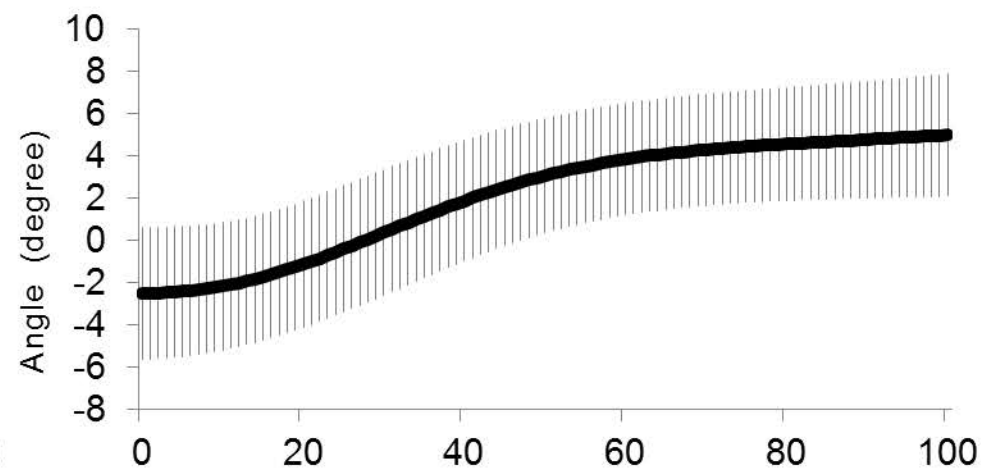


Correlation between rearfoot ER/IR and knee ADD/ABD



Correlation between rearfoot ER/IR and knee IR/ER

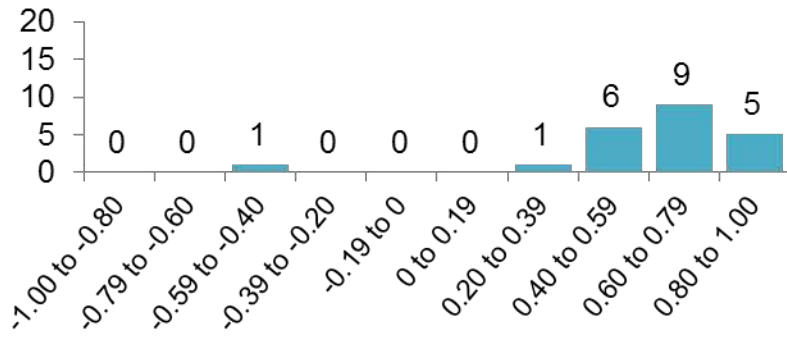


Hip ADD(+)/ABD(-)**Hip IR(+)/ER(-)****Knee ADD(+)/ABD(-)****Knee IR(+)/ER(-)****Rearfoot EVE(+)/INV(-)****Rearfoot ER(+)/IR(-)**

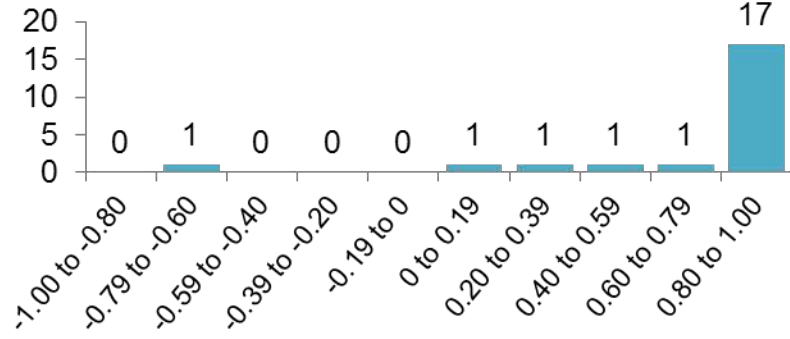
Landing phase (%)

Landing phase (%)

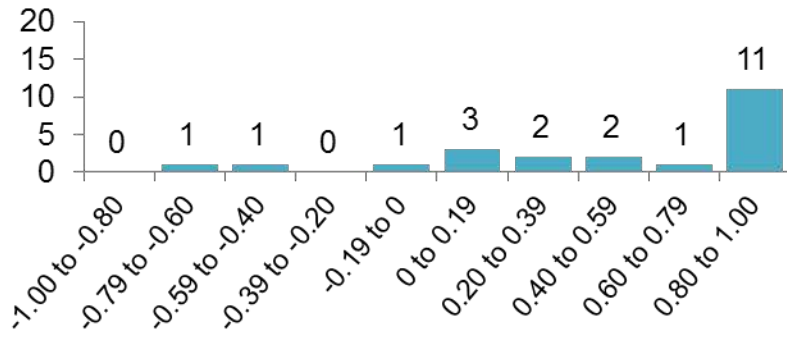
Correlation between rearfoot EVE/INV and hip ADD/ABD



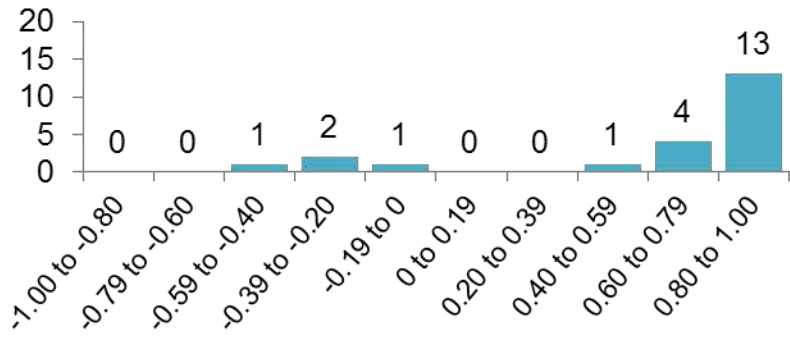
Correlation between rearfoot EVE/INV and hip IR/ER



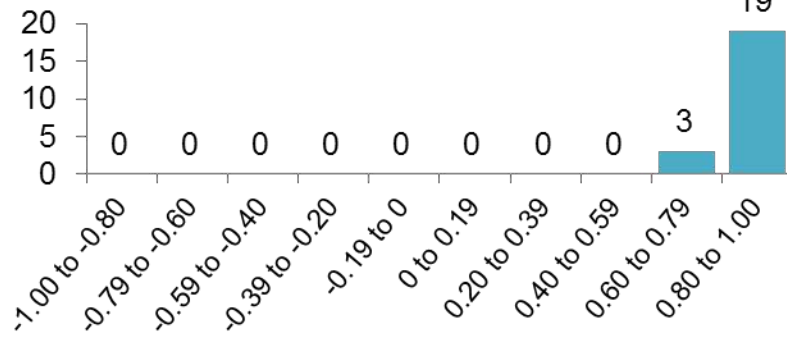
Correlation between rearfoot ENV/INV and knee ADD/ABD



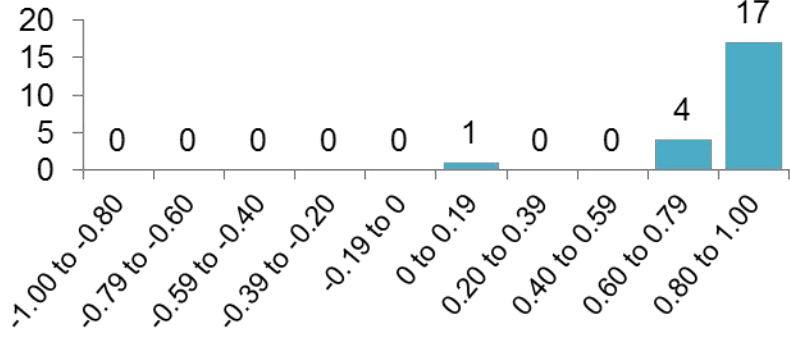
Correlation between rearfoot EVE/INV and knee IR/ER



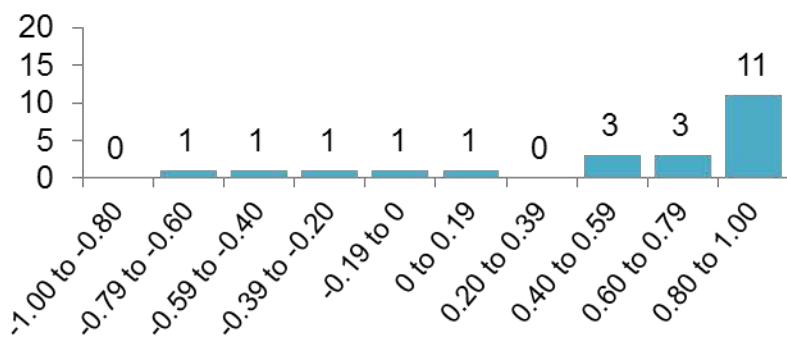
Correlation between rearfoot ER/IR and hip ADD/ABD



Correlation between rearfoot ER/IR and hip IR/ER



Correlation between rearfoot ER/IR and knee ADD/ABD



Correlation between rearfoot ER/IR and knee IR/ER

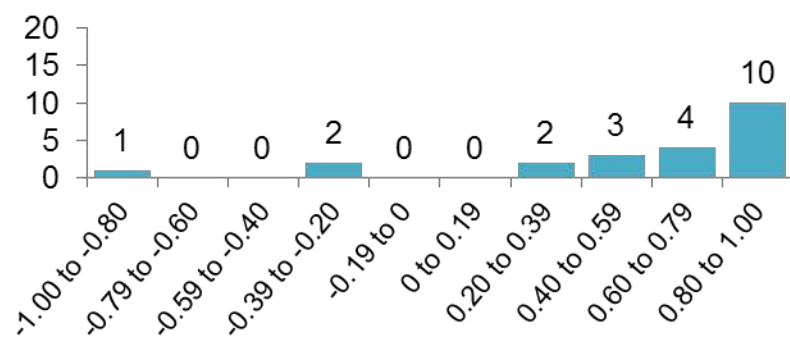


Table 1. Presentation of the correlations and comparisons analyzed during walking and single-leg landing.

| For rearfoot EVE/INV | For rearfoot ER/IR |
|---|---|
| <i>Correlations</i> | <i>Correlations</i> |
| Rearfoot EVE/INV and hip ADD/ABD | Rearfoot ER/IR and hip ADD/ABD |
| Rearfoot EVE/INV and hip IR/ER | Rearfoot ER/IR and hip IR/ER |
| Rearfoot EVE/INV and knee ADD/ABD | Rearfoot ER/IR and knee ADD/ABD |
| Rearfoot EVE/INV and knee IR/ER | Rearfoot ER/IR and knee IR/ER |
| <i>Comparisons of correlation coefficients</i> | <i>Comparisons of correlation coefficients</i> |
| Rearfoot EVE/INV and hip ADD/ABD vs. rearfoot EVE/INV and knee ADD/ABD | Rearfoot ER/IR and hip ADD/ABD vs. rearfoot ER/IR and knee ADD/ABD |
| Rearfoot EVE/INV and hip ADD/ABD vs. rearfoot EVE/INV and knee IR/ER | Rearfoot ER/IR and hip ADD/ABD vs. rearfoot ER/IR and knee IR/ER |
| Rearfoot EVE/INV and hip IR/ER vs. rearfoot EVE/INV and knee ADD/ABD | Rearfoot ER/IR and hip IR/ER vs. rearfoot ER/IR and knee ADD/ABD |
| Rearfoot EVE/INV and hip IR/ER vs. rearfoot EVE/INV and knee IR/ER | Rearfoot ER/IR and hip IR/ER vs. rearfoot ER/IR and knee IR/ER |

Table 2. Median (quartile deviation) of zero-lag cross-correlation coefficients between rearfoot motion and knee and hip joint motion during walking.

| | Rearfoot EVE/INV | Rearfoot ER/IR |
|--------------|--------------------------|--------------------------|
| Hip ADD/ABD | 0.69 (0.06) ^a | 0.84 (0.08) ^b |
| Hip IR/ER | 0.06 (0.22) | -0.26 (0.31) |
| Knee ADD/ABD | 0.37 (0.13) | 0.51 (0.20) ^c |
| Knee IR/ER | -0.04 (0.20) | -0.41 (0.21) |

^a indicates a significantly stronger correlation than the correlations between rearfoot EVE/INV and knee ADD/ABD and between rearfoot EVE/INV and knee IR/ER during walking ($P < 0.001$).

^b indicates a significantly stronger correlation than the correlations between rearfoot ER/IR and knee ADD/ABD and between rearfoot ER/IR and knee IR/ER during walking ($P < 0.001$).

^c indicates a significantly stronger correlation than the correlation between rearfoot ER/IR and hip IR/ER ($P < 0.001$).

Table 3. Mean coupling angles (SD) between rearfoot motion and knee and hip joint motion during walking.

| | Rearfoot EVE/INV | Rearfoot ER/IR |
|--------------|-------------------------|-------------------------|
| Hip ADD/ABD | 41.7 (7.2) ^a | 41.4 (5.8) ^b |
| Hip IR/ER | 41.1 (7.0) ^a | 40.8 (5.9) ^b |
| Knee ADD/ABD | 63.9 (5.1) | 63.8 (4.9) |
| Knee IR/ER | 48.7 (6.0) | 48.7 (4.4) |

^a indicates a significantly smaller than the coupling angles between rearfoot EVE/INV and knee ADD/ABD and IR/ER during walking ($P < 0.001$).

^b indicates a significantly smaller than the coupling angles between rearfoot ER/IR and knee ADD/ABD and IR/ER during walking ($P < 0.001$).

Table 4. Median (quartile deviation) of zero-lag cross-correlation coefficients between rearfoot motion and knee and hip joint motion during single-leg landing.

| | Rearfoot EVE/INV | Rearfoot ER/IR |
|--------------|------------------|--------------------------|
| Hip ADD/ABD | 0.70 (0.13) | 0.92 (0.05) ^a |
| Hip IR/ER | 0.89 (0.07) | 0.92 (0.07) |
| Knee ADD/ABD | 0.79 (0.36) | 0.80 (0.23) |
| Knee IR/ER | 0.87 (0.13) | 0.79 (0.21) |

^a indicates a significantly stronger correlation than the correlation between rearfoot ER/IR and knee IR/ER during single-leg landing ($P = 0.001$).

Table 5. Mean coupling angles (SD) between rearfoot motion and knee and hip joint motion during single-leg landing.

| | Rearfoot EVE/INV | Rearfoot ER/IR |
|--------------|-------------------------|-------------------------|
| Hip ADD/ABD | 36.8 (8.9) ^a | 41.2 (6.4) ^b |
| Hip IR/ER | 32.0 (7.9) ^a | 36.8 (6.9) ^b |
| Knee ADD/ABD | 48.3 (9.1) | 53.4 (9.3) |
| Knee IR/ER | 46.8 (10.7) | 52.5 (10.0) |

^a indicates a significantly smaller than the coupling angles between rearfoot EVE/INV and knee ADD/ABD and IR/ER during single-leg landing ($P < 0.001$).

^b indicates a significantly smaller than the coupling angles between rearfoot ER/IR and knee ADD/ABD and IR/ER during single-leg landing ($P < 0.001$).