Knee Kinematic Coupling in Males and Females: Open and Closed-Chain Tasks

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The purpose of this study was to compare the magnitude of knee kinematic coupling between genders and among open- and closed-chain tasks. A secondary purpose was to compare the consistency of knee kinematic coupling between genders and among open- and closed-chain tasks. Vector-coding methods were used to quantify coupling in the sagittal and transverse planes of the knee between full extension and 20 degrees of flexion as 10 males and 10 females walked, ascended and descended stairs, and performed a passive pendulum leg drop. An ANOVA showed no main effect of gender. There was a main effect of task, where coupling during the stance phase of walking was significantly greater than each of the other tasks. Intraclass correlation values suggested that males were slightly more consistent than females. A general lack of divergence between genders may be related to the tasks analyzed in this study. It is possible that more strenuous tasks may elicit larger differences.

Keywords: knee coupling, gait, stair climbing

Coupling of motions both between and within anatomic joints has been examined frequently in the literature. Some studies hypothesize that discoordinated coupling patterns may be indicative of injury susceptibility (Miller et al., 2008), whereas others have focused on the variability of coupling patterns as a mechanistic link to injury (Dierks & Davis, 2007; Pollard et al., 2005). Coupling of knee sagittal and transverse plane motion is of interest due to the fact that kinematic alterations in these motions are associated with several common injuries. These injuries include iliotibial band syndrome, patellofemoral pain syndrome, tibial stress fracture, and rupture of the anterior cruciate ligament (Davis et al., 2003; Ferber et al., 2010; Milner et al., 2006; Myer et al., 2005; Noehren et al., 2007). The coupling of sagittal and transverse plane motion at the knee is mainly imposed by anatomical constraints in that the medial femoral epicondyle is, on average, 1.7 cm longer than the lateral (Nordin & Frankel, 2001). In order for the tibio-femoral joint to maintain congruence throughout the range of motion, the tibia tends to rotate externally with respect to the femur during knee extension. This movement pattern is reversed with knee flexion. Hamill et al. have suggested that deviations from normal knee kinematic coupling can cause excessive strains within the knee ligaments, such as the anterior cruciate ligament, as well as excessive stress on the cartilage during weight-bearing activities (Hamill et al., 1999).

An individual’s specific coupling pattern is dependent upon their anatomy, including both bony contours and ligamentous structures. These are known to vary between genders, with females tending to have a smaller femoral notch and increased ligamentous laxity (Rozzi et al., 1999; van Eck et al., 2010). While it is unclear how these anatomic and neuromuscular discrepancies between genders should be attributed to differences in movement patterns, these divergences have been linked to elevated knee injury rates in females. For examples, anterior cruciate ligament rupture has a noncontact incidence rate that is 2–3 times higher in females than in males (Waldén et al., 2011). Pollard et al. (2005) suggested that one possible reason for this increased incidence is a 46% decrease in the variability of the coupling mechanism in females during cutting movement tasks. The authors proposed that the decreased flexibility of their system may limit females’ ability to deal with environmental perturbations during athletic tasks. Pollard et al. (2005) focused upon gender differences during cutting. However, there may also be a gender discrepancy in the variability, as well as the magnitude, of knee kinematic coupling during other tasks, such as walking and stair climbing. In addition, it is not clear whether any dissimilarities should be attributed

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purely to gender differences, or whether different types of tasks may also contribute to differences in movement patterns at the knee. This may be elucidated by comparisons of both open- and closed-chain tasks between genders. Typical closed-chain tasks, such as the stance phases of walking or stair ascent and descent, require concentric or eccentric muscle contractions across the knee. During open-chain motions, momentum is acting to pull the limb forward, such as knee extension during the terminal swing phase of gait. In open-chain activities, the tibia is thought to rotate with respect to a stable femur, whereas during closed-chain activities the femur rotates on a stable tibia.

A clear grasp of joint knee kinematic coupling in healthy individuals is an important step in understanding the etiology of knee injury in both males and females. It is unclear whether the magnitude or variability of this coupling is affected by gender or by task. Therefore, there were two purposes of this study: (1) to compare the magnitude of knee kinematic coupling between genders and among tasks and (2) to compare the intraindividual consistency of knee kinematic coupling between genders and among tasks. No interactions were expected, although it was hypothesized that both the magnitude and consistency of knee kinematic coupling would be affected by gender and task.

**Methods**

An a priori power analysis was conducted for a two-way mixed factors analysis of variance (Park & Schutz, 1999). Ten individuals per group were found to be sufficient to detect a difference based upon a clinically meaningful effect size of 0.6, correlation of 0.8 among five repeated tasks, alpha equal to 0.05, and beta equal to 0.2. Therefore, 10 males (31.6 ± 9.1 years; 1.8 ± 4.6 m; 82.1 ± 15.9 kg) and 10 females (32.5 ± 7.7 years; 1.6 ± 5.6 m; 58.5 ± 4.1 kg) were recruited to participate in this institutionally approved study. All individuals were healthy with no history of pathology/injury to the spine and lower extremities, nor any systemic, metabolic, neurologic, or musculoskeletal disease that would affect lower extremity function. Before completing the data collection protocol, all subjects provided informed consent.

Retroreflective markers were placed on the pelvis, thighs, shanks, and feet of each participant. Markers were placed on specific anatomic landmarks, as well as generalized tracking locations on the thigh and shank, to construct a six-degree-of-freedom model of the lower body (see Figure 1). The locations of these markers were tracked at 100 Hz using a 12-camera motion analysis system (Motion Analysis Corp.; Santa Rosa, CA). Euler decomposition methods were used to calculate the rotation of the shank with respect to the femur in the sagittal, frontal, and transverse planes in that order, respectively. Data were collected as the participant completed six acceptable trials of each of the following tasks: a passive pendulum drop, walking, ascent of three stairs, and descent of three stairs. Walking was subsequently divided into stance and swing phases. With the exception of the pendulum drop, all tasks were performed at self-selected speeds. The pendulum drop involved placing the participant in a semi-reclined position (40° of hip flexion). Next, an investigator raised the foot to achieve full knee extension, and then dropped the foot. The foot was allowed to oscillate passively until it came to rest. During testing, the participant’s thigh was supported and their knees and lower legs were completely off the table’s edge so that their feet were free to swing without touching the ground (see Figure 2). This semi-reclined position was chosen so that the hamstrings would be slack when the knee was extended. The passiveness of this task was confirmed by the presence of no greater than minimal quadriceps or medial hamstrings activity, as measured using surface electromyography (Motion Laboratory Systems; Baton Rouge, LA) during testing. Before testing began, maximal voluntary isometric contractions were collected for each muscle to determine reference maximum voltage values. During testing, a physical therapist quantitatively confirmed minimum muscle activity using the comparisons to maximum reference values. Since the pendulum drop...
was performed under controlled passive conditions, it was considered a gold standard for passive motion.

Right-side data were analyzed for each subject. Video data were filtered at 6 Hz using a fourth-order two-way Butterworth filter. Sagittal and transverse plane knee joint angles were calculated using Visual 3D (C-Motion; Rockville, MD) for each of five tasks: pendulum drop, swing phase of walking, stance phase of walking, stair ascent, and stair descent.

Angle-angle plots were then constructed from the sagittal and transverse plane knee angle data. Vector coding methods based on those used by Heiderscheit and colleagues (2002) were used to quantify the kinematic coupling at this joint. This method quantifies an outcome measure in degrees to describe the angle, with respect to horizontal, between sequential data points. A coupling value of 45° indicates that the two joints or planes of interest rotated the same amount in the time interval between the two events of interest. A deviation from 45° indicates that one joint or plane rotated more than the other during the time interval. For the purposes of this study, a value greater than 45° indicated more sagittal plane motion and a value less than 45° indicated more transverse plane motion. For each task, the mean of the coupling was calculated between sequential data points for each of six trials. The mean angle between all sequential data points was then calculated to represent the average coupling in the first 20° of knee flexion. As shown in Figure 3, the angles between sequential data points can vary over time. Therefore, vector coding is typically quantified over small, discrete ranges of motion to minimize the effect of averaging (Dierks & Davis, 2007; Pollard et al., 2005). A specific range of motion between full extension and 20° of knee flexion was examined to focus specifically on the range that minimized potential joint motion reversals, which can lead to discontinuities in vector coding values.

The mean coupling values were then used to test the hypotheses. For the first hypothesis, an individual’s

Figure 2 — The passive pendulum drop task was performed with the participant semi-reclined and with their knees and lower legs off the table so that their feet were free to swing without contacting the ground. Lack of muscle activity was qualitatively confirmed with electromyography on the quadriceps and hamstrings.

Figure 3 — A schematic curve to describe the vector coding method for calculation of knee kinematic coupling value, where the angle with respect to horizontal was calculated between each sequential data point (dashed line). The mean coupling value was determined as the average angle between all sequential data points.
coupling values were averaged among the six trials for a given task. A two-way mixed-effect ANOVA was used to compare the magnitude of coupling between genders and among tasks. A significant ANOVA was followed by post hoc pairwise comparisons. A value of $p < .05$ was considered significant. For the second hypothesis, intraclass correlation values (ICCs: 2,k) were calculated among the six trials for each task and gender separately. The ICC values were then compared descriptively, and a minimum difference of 10% between genders and/or tasks was operationally defined as clinically relevant.

### Results

As expected, all kinematic coupling values were less than 45°, which suggests that there was always more motion in the sagittal plane than the transverse plane. The results of the ANOVA showed no interaction in knee coupling between task and gender ($p = .85$). There was no main effect of gender ($p = .53$); however, there was a main effect of task ($p < .01$). Follow-up testing showed that coupling during the stance phase of walking was significantly greater than during each of the other tasks ($p < .01$ for all). As shown in Figure 4, the stance phase of walking exhibited coupling values that approached 40°, which indicates that this task resulted in sagittal and transverse plane motions that were close to a 1:1 ratio. Conversely, the other tasks exhibited average coupling values between 10 and 20°, which indicates that these tasks require much less transverse motion as the knee moves through the same range of sagittal plane motion.

The results of the reliability analysis are shown in Table 1. For the pendulum drop and the swing and stance phases of walking, males tend to be slightly more consistent than females, although the differences were less than 6%. Differences between genders were much larger for the stair tasks, where males were more consistent at performing stair ascent and females were more consistent at performing stair descent.

### Discussion

The purpose of this study was to compare knee kinematic coupling between genders during different tasks. This was done with the aim of elucidating whether knee coupling is different between genders. The results indicated that there was no effect of gender on coupling for any of the tasks. This finding was unexpected as males and females have been shown to have differences in movement patterns (Ferber et al., 2003; Waldén et al., 2011). However, it is possible that the tasks chosen in this study may not have been sufficiently challenging to elicit the gender differences related to athletic injury. The tasks chosen in this study more closely mimicked those accomplished during typical activities of daily living. While this work suggests that research on this type of knee kinematic coupling can likely be generalized to both genders regardless of the experimental cohort, future studies should consider the addition of more challenging tasks, such as running, jumping, or cutting, to confirm that there are no gender differences in kinematic coupling. Conversely, this similarity between genders may be used to support the notion that the coupling values described in this work can be considered representative of typical coupling patterns in healthy adults. These values can then be used for comparisons to pathologic populations, such as those who are osteoarthritic and injury susceptible.

The comparisons between the tasks chosen in this study showed that knee coupling motions during the stance phase of walking were significantly different from any other task. The average walking stance-phase coupling values approached 45°, which suggests that the amount of transverse plane motion at the knee was nearly equal to that in the sagittal plane. The remaining tasks all exhibited similar values to each other, suggesting that there was a greater rate of sagittal plane motion than transverse plane motion during that joint range.

![](Figure 4 — Mean coupling values for males and females during each task. Error bars are one standard deviation from the mean. The stance phase of walking was significantly (*) more closely coupled than all other tasks.)

<table>
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<tr>
<th>Table 1</th>
<th>Intraclass correlation values (2,k) for the mean coupling values from the six repeated trials within each task, between genders</th>
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<tr>
<td></td>
<td>Pendulum</td>
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<td>Males</td>
<td>0.97</td>
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<td>Females</td>
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The discrepancy between the stance phase of walking values and the open-chain tasks values may be due to the large levels of muscular activity and articular cartilage compression that occurs during the early loading phase of stance examined in this study. Conversely, as open-chain activities, both the swing phase of walking and the pendulum drop induced little to no bone surface compression. In addition, by design, there was no muscular activity during the pendulum drop. This finding is supported by work by Blankevoort (Blankevoort et al., 1988), who showed that tibial external rotation with knee extension is less affected by the passive joint structures than by external loading through the joint. The difference in coupling between the stance phase of walking and the other closed-chain tasks (stair ascent and descent) was more surprising. It is possible that this difference can be attributed to motion of the ankle during simultaneous knee motions examined in this study. In level walking, the heel typically strikes the ground first, whereas for both stair ascent and descent there is forefoot initial contact. In addition, during the loading response phase of walking the ankle undergoes plantar flexion, whereas during stair ascent/descent the ankle undergoes dorsal flexion (see Figure 5). These differences may lead to altered ankle inversion-eversion kinematics during this initial loading phase. Due to the articulating surfaces between the talus and the tibia, altering the ankle inversion/eversion kinematics can affect transverse tibial rotation, as they are known to be coupled motions (Inman, 1976).

The consistency of coupling was generally very high for both genders across all tasks. In both males and females, ICC values were greater than 0.85 for the stance and swing phases of walking, as well as the pendulum drop. There was a divergence of consistency when analyzing the stair negotiation tasks to suggest that males are more consistent in coupling during stair ascent, while females are more consistent during stair descent. The cause of this is unclear at this point. However, this divergence may be related to the fact that stair negotiation was the most challenging task posed in this study and may have imposed differences in muscle activation patterns between males and females. This paradigm may, in part, explain the inconsistencies between this study and work by Pollard et al. (2005), who found significant differences in the variability of knee sagittal and transverse plane motions between males and females. Pollard et al. specifically examined cutting tasks, which is much more demanding than those included in the current study. In addition, the previous work quantified the standard deviation as a measure of variability, whereas the current investigation examined intraclass correlations as a measure of consistency.

It should be noted that the knee does not necessarily move in a smooth trajectory of knee flexion coupled with knee internal rotation (and vice versa). This is evident in Figure 3, which shows that, throughout a trial, the relative rate of transverse plane motion increases with larger knee flexion values. Thus, there is not a steady rate of

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**Figure 5** — A schematic depiction of the initial contact (circled) during level walking and stair climbing. Three representative trials from each show that the direction of ankle rotation during the initial loading phase (shaded region) was reversed in the two tasks.
coupling between the sagittal and transverse planes. It is not clear, however, how much of these fluctuations should be attributed to skin motion artifact, marker placement errors resulting in cross-talk between the sagittal and transverse plane axes (Ramsey et al., 2003), and/or errors from matrix decomposition.

In fact, the limitations stated above may affect all of the findings in this paper. It is likely that the implementation of a passive motion capture system to measure the kinematics of relatively fit individuals with low body mass indices enhanced the chances of capturing true kinematic knee coupling values. Nevertheless, in the absence of bone-pin markers, skin motion artifact is a limitation of any motion analysis study. Furthermore, this work analyzed transverse plane motions that are innately small and are the third in order of matrix decomposition. Finally, this study focused upon a limited range of motion (between 0 and 20° of knee flexion) in young, healthy adults. It remains to be seen whether these kinematic knee coupling values change with different functional ranges or increasing age, or are affected by pathology.

Ultimately, the findings of this study suggest that the magnitude of knee kinematic coupling does not vary greatly between genders. In terms of consistency, there may be a discrepancy between the ability of males and females to perform stair ascent and descent tasks. However, males were more consistent during stair ascent and females during stair descent. The implications of this finding are unclear; therefore, further research should be conducted to elucidate this difference. In terms of differences between tasks, the stance phase of walking was more closely coupled than the other four tasks that reflect activities of daily living. However, large differences in the consistency of coupling among the tasks do not seem to exist.

References