Patellar Tendinopathy Alters the Distribution of Lower Extremity Net Joint Moments During Hopping

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The purpose of the current investigation was to test the hypothesis that subjects with patellar tendinopathy would demonstrate altered sagittal plane joint moment contributions during hopping tasks. Fourteen subjects (7 patellar tendinopathy, 7 controls) participated. Sagittal net joint moments of the lower extremity, total support moment, and joint contributions to the total support moment were calculated while subjects hopped continuously at a self-selected frequency and at 1.67 Hz. Significant differences were observed for contributions to the total support moment ($p = .022$). When averaged across hopping frequencies, subjects with patellar tendinopathy demonstrated greater hip contribution ($p = .030$) and lesser knee contribution ($p = .006$) compared with the control subjects. Shifting the workload away from the knee and toward the hip may result in a detrimental increase in hip demand and potentially harmful long-term effects on the articular cartilage of the hip.

Keywords: total support moment, volleyball, net joint moment

A hop is a task that has been extensively studied and has the potential to reveal important information regarding intersegmental dynamics (Butler et al., 2003; Farley et al., 1998; Ferris & Farley, 1997). During a hop, the hip, knee and ankle work in concert to accomplish the task of moving the center of mass against gravity. This task requires complex coordination to achieve sufficient torque output from each of the lower extremity joints to perform the task. These individual joint mechanics are influenced by several external and internal factors, including hopping-surface material properties, training experience, fatigue, and injury status, among others (Moritz et al., 2004; Orishimo & Kremenic, 2006; Webster et al., 2004; Kuitunen et al., 2002). For example, subjects demonstrated increased knee flexion angles and quadriceps muscle activation when hopping on hard surfaces relative to soft surfaces (Moritz et al., 2004). Others have shown that a fatiguing bout of exercise resulted in increased ankle moments, decreased knee moments, and decreased ankle and knee stiffness compared with nonfatiguing conditions (Orishimo & Kremenic, 2006; Kuitunen et al., 2002). Following anterior cruciate ligament reconstructive surgery, knee flexion range of motion and knee extensor moments are decreased on the reconstructed knee compared with the contralateral side during hopping (Webster et al., 2004). Hence, hopping is a suitable activity for studying intersegmental mechanics in the presence of a lesion in the knee extensor mechanism.

A method for analyzing the interplay among the joints of the lower extremity is to assess the relative contributions of each lower extremity joint to the total support moment generated during a movement (Winter, 1980). The total support moment is an antigravity measure of the total torque demand experienced by the lower extremity to prevent collapse. It is calculated by summing the net sagittal plane moments of the lower extremity (i.e., ankle, knee, and hip) (Hof, 2000). The total support moment is strongly correlated to both vertical work ($r = .979$) and power ($r = .805$) during athletic tasks (Flanagan & Salem, 2005) and demonstrates high repeatability across slow, natural and fast walking trials, as well as stair ascent and descent (Winter, 1983; McFadyen & Winter, 1988). Furthermore, the support moment has a considerably lower coefficient of variation compared with individual joint moments (Winter, 1984; Hof, 2000). This was demonstrated by Webster and colleagues (Webster et al., 2004), who reported that individuals following anterior cruciate ligament reconstructive surgery had significant differences in knee moments but no differences in support moments during hopping. Due to its stable nature, the support moment is a very appealing measure of intersegmental dynamics to study the influence of a musculotendinous lesion on joint mechanics. It is the
relative contribution of each lower extremity joint, to the total support moment, that has the potential to provide unique information regarding the self-selected, imposed, adaptive, and compensatory movement strategies required to accomplish complex, coordinated, multijoint tasks.

Pain and/or tendinopathies are factors known to influence movement patterns and alter joint kinetics (Bisseling et al., 2007; Richards et al., 2002). Tendinopathy is a general term that describes all pathologies that arise in and around tendons. These include tendinitis, tendinosis, and paratenonitis (Khan et al., 1999). In the lower extremity these pathologies are common at the patellar tendon, Achilles tendon, and posterior tibial tendon (Khan et al., 1999). Patellar tendinopathy has been defined as activity-related, anterior knee pain associated with focal patellar tendon tenderness (Warden & Brukner, 2003). The prevalence of patellar tendinopathy in athletes is high with over 22% of all athletes having a history of current or previous symptoms (Lian et al., 2005). The sports with the highest prevalence of symptoms are volleyball (45%) and basketball (32%) (Lian et al., 2005). It has been reported that individuals with patellar tendinopathy are more likely to exhibit decreased knee joint kinetics when compared with healthy controls during a bilateral drop jump (Bisseling et al., 2007). Furthermore, deeper knee flexion angles during landing and a higher magnitude of vertical ground reaction force during takeoff have been shown to be significant predictors of individuals with patellar tendinopathy during the volleyball spike jump (Richards et al., 2002).

Despite recent studies on this topic, it remains unclear how tendinopathy, affecting one link of the three-joint system, would affect the individual lower extremity net joint moments and total support moment during a repeated multijoint task. The purpose of the current investigation was to quantify the relative contributions of the hip, knee and ankle to the total support moment, associated with self-selected- and imposed-frequency hopping tasks, in athletes with and without patellar tendinopathy. It is hypothesized that subjects with patellar tendinopathy would demonstrate altered sagittal plane moment contributions during hopping when compared with healthy controls, shifting the relative effort away from the knee and to the hip and/or ankle.

Methods

Subjects

Two groups of subjects were recruited for this study. Seven men with a history of patellar tendinopathy served as the experimental group and seven men without a history of knee pain or injury constituted the control group. All subjects were elite volleyball players either playing at the collegiate (Los Angeles-area universities) or professional levels.

The following criteria were used for inclusion purposes and to operationally define “patellar tendinopathy”: (1) history of pain located completely within the patellar tendon, confirmed by palpation, (2) history of pain with tendon loading tasks (jumping, squatting, etc.) for duration of >3 months and (3) currently competing without self-reported activity limitations related to patellar tendon pain. Subjects were excluded if they had any of the following: (1) history of knee surgery or trauma, (2) knee effusion, or (3) knee joint instability. The control group was selected based on the same criteria as the experimental group, except that these subjects had no history of current or previous knee pain of any kind.

Instrumentation

Three-dimensional motion analysis was performed using a computer aided video motion analysis system (Vicon, Oxford Metrics Ltd. Oxford, England). Kinematic data were sampled at 250 Hz. Ground reaction forces were collected at 1500 Hz using an AMTI force platform (Model #OR6–6–1, Newton, MA, USA) embedded in the laboratory floor. A digital quartz metronome (Model# QT5, Quik Time) was used for pacing purposes.

Procedures

All testing took place at the Musculoskeletal Biomechanics Research Laboratory at the University of Southern California. Procedures were explained to each subject and each provided informed consent, in accordance with the Institutional Review Board of the University of Southern California. The subject’s age, height, and weight were recorded. For all subjects with patellar tendinopathy the lower extremity with a history of pain coincided with the subject’s dominant lower extremity (i.e., right knee pain for all right-handed subjects), and so it was the dominant lower extremity that was tested. Similarly for control subjects, the dominant lower extremity was tested.

Triads of rigid reflective tracking markers were securely placed on the lateral surface of the subject’s thigh, leg and heel shoe counter of the dominant lower extremity. Additional tracking markers were placed on each anterior superior iliac spine, iliac crest, and the L1/ S1 interspinous space. Calibration markers were placed bilaterally on the greater trochanters, medial and lateral femoral epicondyles, medial and lateral malleoli, and 1st and 5th metatarsal heads, to locate the segment origins. Once the markers were placed, a standing trial was captured. After the standing trial, the calibration markers were removed. The tracking markers remained on the subject throughout the data collection session.

Subjects were positioned on the force platform and instructed to continuously hop on their dominant lower extremity at a self-selected frequency, while holding their arms crossed about their chest. They were instructed to “clear your foot” on each successive hop and remain within the boundaries of the force platform (51 cm long × 46 cm wide). They received verbal instructions during data collection if their foot migrated close to the edge of the boundary during the hopping trials. Once the subject reached a steady pace of hopping, data were collected for
20 successive hops. A successful hop was considered one in which the foot of the subject landed completely within the boundary of the force platform, followed by the foot completely leaving the force platform (as measured by the ground reaction forces). No mention of maximal or submaximal effort was discussed with the subjects; however, the subjects’ self-selected rate of hopping indicated a submaximal effort.

Following self-selected hopping, the subjects repeated the procedure using an externally imposed frequency of 1.67 Hz, or 100 hops per minute—regulated via a digital audio and visual metronome. Pilot subjects reported an increase in perceived knee effort with this frequency. In addition, controlling the rate of hopping imposes a restriction on movement variability. Average hopping rate of trials using the imposed hopping frequency were significantly less than the average self-selected hopping rate of trials using the imposed hopping frequency. In addition, controlling the rate of hopping frequency of 1.67 Hz, or 100 hops per minute—regulated via a digital audio and visual metronome. Pilot subjects reported an increase in perceived knee effort with this frequency. In addition, controlling the rate of hopping imposes a restriction on movement variability. Average hopping rate of trials using the imposed hopping frequency were significantly less than the average self-selected hopping frequency ($p < .001$).

### Data Analysis

Visual 3D software (C-Motion, Rockville, MD) was used to quantify lower extremity net joint moments. Markers were identified manually within the Vicon Workstation software and then imported into Visual 3D. In Visual 3D, the lower extremity was modeled as 6-degree-of-freedom segments (foot, leg, thigh, and a pelvis). Only the stance phase (as determined by the ground reaction force) of the hopping cycle was used for analysis.

Kinematic and ground reaction force data were used to calculate sagittal plane hip, knee and ankle net joint moments (i.e., internal moments) using standard inverse dynamics equations. To facilitate comparisons of moments between groups, these data were normalized to body mass. For statistical comparisons, average normalized net joint moments during the stance phase of each hop, averaged over 20 hops, were recorded. In addition to the individual net joint moments, the total support moment was calculated as the sum of the averaged hip extensor, knee extensor, and ankle plantar flexor net joint moments (Winter, 1980; Flanagan & Salem, 2005). The relative contribution of each net joint moment to the total support moment was calculated using the following formula:

$$C_{\text{net}} = \left( \text{aNJM}_{\text{net}} / \text{TSM} \right) \times 100$$

where $C$ is the contribution of the hip, knee, or ankle; aNJMs is the averaged net joint moment of the hip, knee, or ankle as described above; and TSM is the total support moment.

### Statistical Analysis

To determine if average net joint moments of the lower extremity varied between groups across hopping frequencies, $2 \times 2$ (group $\times$ hopping frequency) multivariate repeated-measures ANOVAs were performed for the hip, knee, and ankle. This analysis was repeated for the total support moment and the contributions to the total support moment. For all ANOVA tests, significant main effects were reported if there were no significant interactions. If a significant interaction was found, the individual main effects were analyzed separately using independent samples $t$ tests. Hopping frequency and duty cycle (stance time/flight time) were compared between groups for self-selected hopping using an independent samples $t$ test. Statistical analyses were performed using SPSS statistical software (Chicago, IL), with a significance level of $p \leq .05$.

### Results

Subject age, height, and mass are listed in Table 1. No significant group differences were observed in these characteristics. For self-selected hopping, average frequencies were similar between groups ($1.89 \pm 0.30$ vs. $2.04 \pm 0.17$ Hz; $p = .110$; for the patellar tendinopathy and control groups, respectively). Furthermore, duty cycles (stance times/flight times) for groups were similar as well ($2.60 \pm 0.76$ vs. $2.42 \pm 0.64$; $p = .661$).

No group effect, frequency effect, or interaction was found for the average total support moment generated across hopping tasks ($p > .05$; Figure 1). In contrast, the individual contributions of the hip, knee, and ankle to the total support moment, demonstrated a significant group effect across hopping frequencies ($p = .022$). When averaged across hopping frequencies, subjects with patellar tendinopathy demonstrated greater hip contribution ($20.2 \pm 8.4$ vs. $12.2 \pm 2.8$%; $p = .030$), less knee contribution ($23.2 \pm 5.2$ vs. $24.8 \pm 6.3$%; $p = .006$), and similar ankle contribution ($53.7 \pm 6.6$ vs. $54.6 \pm 6.6$%; $p = .773$), compared with the control subjects (Figure 2). In addition, a significant frequency effect was observed ($p = .018$). When averaged across groups, the externally imposed hopping frequency of 1.67 Hz resulted in greater knee contribution ($32.3 \pm 6.6$ vs. $25.4 \pm 8.0$%; $p = .004$), less ankle contribution ($51.8 \pm 5.7$ vs. $57.3 \pm 7.7$%; $p = .018$), and similar hip contribution ($15.9 \pm 6.5$ vs. $17.2 \pm 8.2$%; $p = .481$), compared with the self-selected frequency.

A significant group effect was observed for average net joint moments across hopping frequencies ($p = .018$). However, univariate analysis revealed that no single variable was statistically different between groups even though the average moments varied. When averaged across frequencies, the patellar tendinopathy group generated a trend toward a greater average hip extensor moment (72%; $p = .078$), and less knee moment (23%; $p = .082$) (Figure 3). No frequency effect was observed ($p > .05$).

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<th>Table 1 Subject age, height, and mass</th>
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<td><strong>Variable</strong></td>
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Figure 1 — Total support moment during self-selected and 1.67 Hz hopping for patellar tendinopathy and control subjects. No significant difference was observed between groups.

Figure 2 — Contribution of joint moments to total support moment during self-selected (A) and 1.67 Hz (B) hopping for patellar tendinopathy and control subjects. *Significant group effect was observed across hopping frequencies ($p = .022$)
Discussion

Our findings demonstrate that subjects with patellar tendinopathy performed a continuous hopping task by adopting a movement strategy that requires greater hip extensor moment and less knee extensor moment. We observed that the relative contribution to the total support moment was particularly discriminative between groups, while the magnitude of total support moment was not different, and the individual net joint moments showed limited trends.

Our results revealed that the relative joint effort of the lower extremity was different between groups. During self-selected hopping the patellar tendinopathy group demonstrated a considerable hip-dominant strategy, with nearly twice the hip joint effort (21% vs. 12%) when compared with the controls. In addition, they had significantly less knee contribution (22% vs. 29%) to the overall support moment.

The results are in support of previous findings that have observed decreased knee contribution to total support moment in a group of individuals following ACL rupture (Hurd & Snyder-Mackler, 2007). In this study, the investigators reported that subjects were “off-loading” their knee in an attempt to spare the pathologically affected joint. It should be noted that the task investigated in the current study was relatively low-effort level compared with the cohort’s typical exercise intensities. Patellar tendinopathy subjects did not report pain during either of the hopping tasks. Despite this, subjects chose to use a strategy that decreased the demand on the knee.
In response to the externally imposed hopping frequency (1.67 Hz) both tendinopathy and control subjects altered their relative contributions to the total support moment. This resulted in a significant increase in knee contribution (p = .004), less ankle contribution (p = .018), with no difference in hip contribution (p = .418) to the total support moment for both groups. In our previous unpublished pilot studies, it was observed that an individual’s self-selected frequency was typically higher than 1.67 Hz (2.02 Hz for the current study) and slowing the hopping rate below the self-selected rate resulted in increased knee net joint moments and reports of perceived increased knee effort from the subjects. Consistent with pilot data, control subjects increased their knee contribution from 29% to 37%. Included with this adjustment was a decrease in ankle contribution (from 59 to 50%) without a change in the hip contribution. Similar adjustments were made in the patellar tendinopathy group; however, the increase in the knee contribution and decrease in the ankle contribution were slightly less (22 to 28% and 57 to 53%, respectively). When comparing groups at 1.67 Hz hopping, the results remain similar to the self-selected hopping condition, where tendinopathy subjects demonstrated greater hip contribution (19% vs. 13%) and lesser knee contribution (28% vs. 37%) with no significant difference in ankle contribution.

No differences in total support moment were found in the current study. When averaged across frequencies, the total support moment of subjects with patellar tendinop- athy was within 4% of the control subjects. These findings corroborate the findings by Williams and colleagues who reported that while leg and knee stiffness values differed between groups (high and low arch) the total support moment remained unchanged (Williams et al., 2004).

With regard to net joint moments, subjects with patellar tendinopathy generated greater hip net joint moments when compared with controls. When averaged across hopping frequencies, patellar tendinopathy subjects generated nearly twice the average hip net joint moment when compared with controls. Post hoc analysis revealed that these differences were greatest during self-selected hopping (96% difference) as opposed to 1.67 Hz hopping (51% difference). These findings are in contrast to a study performed by Bisseling and colleagues (Bisseling et al., 2007). These authors investigated subjects with patellar tendinopathy during a drop jump and reported no difference in hip joint kinetics when compared with controls. These differences may be partially explained by the tasks investigated. In the current study, subjects performed a repeated single leg hopping task that required greater stability, additional planning requirements and fatigue resistance, as opposed to an isolated double limb drop jump that required more maximal effort and power production. In addition, these authors reported peak joint moments, peak joint power and joint work, whereas the current study reported average net joint moments. These results illustrate the importance of examining not only the absolute kinetic parameters of an activity (e.g., average net joint moments), but also the relative contribution of the individual joints to an overall objective—support of body mass against gravity during hopping.

Clinically, these results may have important implications. Shifting the workload away from the knee and toward the hip may result in a detrimental increase in hip demand. Potentially, elevated joint reaction forces from increased moment contribution at the hip could lead to harmful long-term effects on the articular cartilage of the hip. Future studies on the effects of increased hip net joint moments in this population appear warranted. Limitations of the current study include the submaximal task evaluated and a small sample size. The observed differences in joint kinetics during the task of hopping may or may not remain consistent during maximal activities such as explosive jumping or sprinting. Further investigation of these tasks is needed. Finally, it should be noted that although differences in the joint contributions to the total support moment were identified between groups, the small sample size evaluated in the current study may have resulted in a lack of power to reveal significant differences in average hip and knee extensor moments alone (p ≥ 0.08).

In conclusion, subjects with patellar tendinopathy had a greater average hip extensor contribution and lesser knee extensor contribution to the total support moment. These findings were consistent across hopping frequencies. It is important to note that our analysis of the distribution of joint effort to the total support moment revealed important information that standard analyses of the peak or average net joint moments may not have revealed. Future studies investigating joint effort in the presence of pathology may want to consider a similar approach.

References


