The influence of knee alignment on lower extremity kinetics during squats

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Abstract

The squat is an assessment of lower extremity alignment during movement, however there is little information regarding altered joint kinetics during poorly performed squats. The purpose of this study was to examine changes in joint kinetics and power from altered knee alignment during a squat. Thirty participants completed squats while displacing the knee medially, anteriorly, and with neutral alignment (control). Sagittal and frontal plane torques at the ankle, knee, and hip were altered in the descending and ascending phase of the squat in both the medial and anterior malaligned squat compared to the control squat. Ankle and trunk power increased and hip power decreased in the medial malaligned squat compared to the control squat. Ankle, knee, and trunk power increased and hip power decreased in the anterior malaligned squat compared to the control squat. Changes in joint torques and power during malaligned squats suggest that altered knee alignment increases ankle and trunk involvement to execute the movement. Increased anterior knee excursion during squatting may also lead to persistent altered loading of the ankle and knee. Sports medicine professionals using the squat for quadriceps strengthening must consider knee alignment to reduce ankle and trunk involvement during the movement.

1. Introduction

Sports medicine and performance professionals commonly use the squat exercise as a quadriceps strengthening exercise. Squats are also used to visually evaluate knee alignment during movement in a bilateral stance (Kritz et al., 2009; Noda and Verscheure, 2009) because it requires mobility and stability at the ankle, knee, hip, and trunk for optimal performance (Cook et al., 2014). Performance on a squat assessment is also predictive of performance on an entire movement screen (Clifton et al., 2015), indicating that the bilateral squat may be appropriate to identify individuals who may be at increased risk of injury. Despite the growing popularity of the use of bilateral squat assessment, there is little information regarding changes in lower extremity kinetics during commonly observed technique deviations.

Two commonly observed technique deviations during squat performance include excessive medial and anterior knee displacement (Kritz et al., 2009). Medial knee displacement has been associated with altered lower extremity muscle activation patterns (Padua et al., 2012; Slater and Hart, in press), however little is known about the consequences of increased anterior knee displacement. Some have noted increased trunk motion and flexion torque at the hip when anterior knee displacement is restricted during squatting (Fry et al., 2003; List et al., 2013), however there is no current literature examining the way the lower extremity and trunk attenuates the ground reaction forces with excessive knee excursion. Changes in joint power absorption have been noted between soft and stiff landings, indicating that knee position alters lower extremity force attenuation (Devita and Skelly, 1992). Increased anterior or medial knee displacement may result in altered lower extremity joint kinetics and increased involvement of distal and proximal joints to execute the squat movement.

Changes in lower extremity alignment during bilateral squats are also important given the potential for increased patellofemoral contact forces during squatting (von Eisenhart-Rothe et al., 2004; Besier et al., 2005; Mesfar and Shirazi-Adl, 2005; Trepczynski et al., 2012). Previous researchers have noted decreased quadriceps activation and increased gastrocnemius activation with medial knee displacement during bilateral squats (Padua et al., 2012). The increased gastrocnemius activation stabilizes the ankle during peak knee flexion and decreases strain at the anterior cruciate ligament (Hsu et al., 1993; Kvist and Gillquist, 2001; Morgan et al., 2014), which may indicate an unstable knee position with altered lower extremity alignment. Although lower extremity muscle activation...
patterns change from altered knee alignments, little attention has been given to changes in joint torque and power distribution. Current literature suggests that changes in knee alignment during weighted squats decreases internal knee extension torque and increases internal hip extension torque at peak knee flexion, supporting that varying knee alignments may increase proximal joint contribution (Fry et al., 2003). There is no current study, however, identifying changes in lower extremity joint torque and power distribution over the entire squat cycle during a bilateral bodyweight squat. Understanding the way the lower extremity attenuates ground reaction forces with excessive knee excursion is important to appreciate the consequences and behavior of surrounding joints during the movement. Furthermore, a better understanding of lower extremity torque and power distribution with altered knee alignments during the squat will provide clinicians an evidence based approach when evaluating the bilateral squat assessment, similar to the single leg squat and landings (Hewett et al., 2005; Crossley et al., 2011). Therefore, the purpose of this study was to compare changes in joint torque and joint power resulting from altered knee alignment during a bilateral squat. We hypothesized that medial and anterior knee displacement would increase lower extremity torques and joint power in the ankle and trunk during both the descending and ascending phase of the squats compared to a control squat.

2. Methods

2.1. Design

A descriptive, repeated measures laboratory design was used to compare three different squat techniques. The independent variable in this study was squat technique (control, anterior malaligned, and medial malaligned). The dependent variables included lower extremity joint moments and lower extremity and trunk joint power from 0% to 100% of the squat cycle.

2.2. Subjects

Thirty healthy, recreationally active subjects (19 females, 11 males, 21.4 ± 3 years, 170.9 ± 8.8 cm, 66.5 ± 11.9 kg) without self-reported history of lower extremity injury within the past 6 months and no surgical history volunteered. All subjects provided informed consent prior to participating. Study methods were approved by the university’s institutional review board for health science research.

2.3. Instrumentation

Kinematic data were collected using an electromagnetic motion analysis system (Ascension Technology Corporation, Burlington, VT) and sampled at 144 Hz, which has been used previously in squat research (Padua et al., 2012; Slater and Hart, in press) and provides accurate and reliable three-dimensional movement of body segments (Milne et al., 1996). Ground reaction forces were collected using a single force plate (Bertec, Columbus, OH) and sampled at 1000 Hz. Mass-normalized internal joint moments and joint powers were calculated using MotionMonitor software (Innovative Sports Training, Chicago, IL) (Houck et al., 2007). All data were synchronized and exported using MotionMonitor software.

2.4. Procedures

Subjects reported to the laboratory for a single session wearing athletic shoes and athletic clothing. Electromagnetic sensors were placed bilaterally on the dorsum, midshank, and midtigh, the sacrum and T2. Bony landmarks were digitized using the endpoint of a stylus with a fixed electromagnetic sensor. Digitized bony landmarks included left and right anterior superior iliac spines, medial and lateral malleoli, medial and lateral knee joint lines, and L5/S1, T12/L1, C7/T1. Left and right anterior superior iliac spines of the pelvis were digitized to determine the hip joint center of rotation using the Bell method (Bell et al., 1989). Medial and lateral malleoli and knee joint lines were digitized to determine the ankle and knee joint centers. Spinal landmarks were defined as the digitized space between the associated processes (Blackburn and Padua, 2009).

Subjects placed the dominant foot within a single force plate embedded in the floor and the contralateral foot outside of the force plate (Escamilla et al., 2009a,b). The dominant leg was defined as the preferred kicking leg (Brophy et al., 2010). The subject practiced bilateral squats to parallel to become accustomed to the wires from the electromagnetic motion capture system. The subject stood with feet shoulder width apart, toes pointing forward and performed 5 trials of 3 different squat techniques in the following order: A squat with knees intentionally malaligned in the frontal plane (medial malaligned), a squat with the knees intentionally malaligned in the sagittal plane (anterior malaligned), and a squat with the knees in line with the feet (control). Subjects were instructed to squat in a slow, controlled manner, until thighs were parallel with the floor for all 3 squat conditions. Feedback on knee alignment and squat performance was only given during the control squat and included the following statements: Sit back at your heels like you’re sitting in a chair; push your knees out in the bottom of the squat; keep your toes pointing forward (Slater and Hart, in press). The order of the squats was predetermined to limit feedback during squat performance until malaligned squats were completed.

2.5. Data processing and statistical analyses

Kinematic and kinetic data were filtered using a zero-lag fourth-order Butterworth filter at 14.5 Hz then synchronized and reduced to 50 points from full knee extension to peak knee flexion and 50 points from peak knee flexion returning to full knee extension. Combining these two phases represents 100% of the squat cycle so that 50% represents peak knee flexion and 0% and 95% represent full knee extension (Robertson et al., 2008; Padua et al., 2012). Descending phase of the squat cycle was defined as 0–49% and ascending phase of the squat cycle was defined as 50–99%. Internal joint moments were calculated using inverse dynamics. Sagittal and frontal internal joint moments and net joint powers for the dominant limb were calculated using inverse dynamics in MotionMonitor software (Houck et al., 2007) and were mass normalized. Negative joint powers were interpreted as power absorption while positive joint powers were interpreted as power generation (Williams et al., 2012; Nagano et al., 2015). Means and 90% confidence intervals were calculated for each squat technique. Areas in which confidence intervals did not overlap for three or more consecutive percentage points were considered statistically significant (Drewes et al., 2009; Kuenze et al., 2014). Cohen’s d effect sizes were calculated using mean differences and associated pooled standard deviations during periods of the squat cycle when squat techniques (malaligned and control condition) were significantly different.

3. Results

Anterior and lateral knee displacement relative to the starting position (full knee extension) during the different squat techniques are shown in Fig. 1.
3.1. Internal joint moments

3.1.1. Medial malaligned squat

The medial malaligned squat significantly increased internal ankle plantarflexion moment from 9% to 99% of the squat cycle compared to the control squat (Fig. 2). Internal knee extension moment decreased in the medial malaligned squat from 89% to 99% of the squat cycle compared to the control squat (Fig. 2). Internal hip extension moment decreased in the medial malaligned squat from 45% to 52% of the squat cycle and increased 89–94% of the squat cycle compared to the control squat. The medial malaligned squat increased internal ankle eversion moment from 19–40% and 52–60% of the squat cycle and decreased internal ankle eversion moment from 88% to 99% of the squat cycle compared to the control squat (Fig. 2). Internal knee adduction moment increased in the medial malaligned squat from 5% to 99% of the squat cycle compared to the control squat (Fig. 2). Internal hip abduction increased in the medial malaligned squat from 29% to 71% and decreased from 83% to 99% of the squat cycle compared to the control squat (Fig. 2). Effect sizes were large for all differences during the squat cycle (Fig. 3).

3.1.2. Anterior malaligned squat

The anterior malaligned squat significantly increased internal ankle plantarflexion moment from 2% to 99% of the squat cycle compared to the control squat (Fig. 2). Internal knee extension moment decreased from 9% to 25% and 74–99% of the squat cycle and increased from 33% to 66% of the squat cycle compared to the control squat (Fig. 2). Internal hip extension moment decreased in the anterior malaligned squat from 19% to 70% of the squat cycle and increased from 33% to 66% of the squat cycle compared to the control squat (Fig. 2). Internal hip extension moment decreased in the anterior malaligned squat from 19% to 70% of the squat cycle.
and increased from 89% to 99% compared to the control squat (Fig. 2). The anterior malaligned squat increased internal ankle eversion moment from 22% to 86% of the squat cycle compared to the control squat (Fig. 2). Internal knee abduction moment decreased in the anterior malaligned squat from 4–40% and 59–92% of the squat cycle compared to the control squat (Fig. 2). Internal hip abduction moment decreased during the anterior malaligned squat from 5–30%, 40–45%, and 76–95% of the squat cycle compared to the control squat (Fig. 2). Effect sizes were moderate to large for all differences during the squat cycle (Fig. 4).

3.2. Joint powers

3.2.1. Medial malaligned squat

The medial malaligned squat increased ankle power absorption from and power generation from 52% to 98% of the squat cycle compared to the control squat (Fig. 5). Power absorption at the hip decreased in the medial malaligned squat from 25% to 40% of the squat cycle compared to the control squat (Fig. 5). Hip power generation decreased in the medial malaligned squat from 53% to 67% and increased from 80% to 97% of the squat cycle compared to the control squat (Fig. 5). Power absorption at the trunk
increased in the medial malaligned squat from 25% to 31% and power generated at the trunk increased 73–90% of the squat cycle compared to the control squat (Fig. 5). Effect sizes were moderate to large for all differences during the squat cycle (Fig. 6).

3.2.2. Anterior malaligned squat

The anterior malaligned squat increased ankle power absorption from 8–26% and 88–99% of the squat cycle compared to the control squat (Fig. 5). Ankle power generation increased in the anterior malaligned squat from 52% to 86% of the squat cycle compared to the control squat (Fig. 5). Power absorbed at the knee decreased in the anterior malaligned squat from 8% to 24% and power generated at the knee decreased from 77% to 99% of the squat cycle compared to the control squat (Fig. 5). Power generated at the hip decreased from 12% to 32% of the squat cycle compared to the control squat (Fig. 5). Power generated at the hip increased in the anterior malaligned squat from 83% to 99% of the squat cycle compared to the control squat (Fig. 5). Power generated at the trunk decreased from 52% to 59% and increased from 75% to 86% of the squat cycle compared to the control squat.
4. Discussion

The purpose of this study was to examine changes in joint torque and power resulting from medial and anterior knee displacement during a bilateral squat. The results of this study indicate that sagittal and frontal plane knee alignment influences lower extremity joint moments and powers during a squat exercise. Medial knee excursion increased internal plantarflexion torque, ankle eversion torque, knee adduction torque, and hip abduction torque while decreasing knee and hip extension torque. Medial knee excursion also increased ankle and trunk joint power and decreased joint power at the hip. Increased anterior knee excursion increased internal plantarflexion torque and ankle eversion torque and decreased knee and hip abduction torques. Anterior knee excursion also increased ankle joint power and decreased hip joint power compared to a control squat. When knee joint power decreased with anterior knee displacement, trunk joint power increased and when knee joint power increased, trunk joint power decreased.

Increased knee excursion during squatting increased ankle contribution to the movement. Both medial and anterior knee excursion increased internal plantarflexion moment and ankle joint power. Although subjects with dynamic knee valgus often display decreased dorsiflexion range of motion (Bell et al., 2008), these assessments are often completed in unilateral stance or with minimal knee flexion, such as the single leg squat. Previous researchers (Padua et al., 2012; Slater and Hart, in press) investigating bilateral squats have noted increased gastrocnemius activation during squats.

(Fig. 5). Effect sizes were moderate to large for all differences during the squat cycle (Fig. 7).
with medial knee displacement, supporting increased ankle contribution with knee malalignment. This increased gastrocnemius activation during flexed knee stance may be an effort to decrease anterior tibial translation and stabilize the lower extremity (Hsu et al., 1993; Kvist and Gillquist, 2001; Morgan et al., 2014). Alternatively, knee malalignments during squats may be due to gastrocnemius tightness (Bell et al., 2012). Furthermore, ankle joint power absorption and generation increased during both malaligned squat conditions compared to the control condition. Similar increases in ankle power absorption have been noted during gait when moving from a rearfoot to forefoot strike (Williams et al., 2012). This increased power absorption during malaligned squats may be due to the altered center of pressure location at the foot. Changes in knee alignment move center of pressure towards the forehead during the squat (Koh et al., 2015) increasing the moment arm to the ankle and increasing internal plantarflexion torque (Fig. 2) and power absorption (Fig. 5) at the ankle. Maligned squats may be a consequence of poor knee extensor strength, displacing joint torque and power absorption to the ankle joint.

Along with increased ankle contribution, knee malalignments also increased trunk contribution to the squat movement. Restricting anterior knee displacement during a bilateral squat may increase shear forces at the trunk from the vertical trunk position maintained throughout the squat cycle (Fry et al., 2003; List et al., 2013), however the results of this study suggest that too much anterior displacement of the knee may be disadvantageous. The anterior maligned squat increased joint power absorption at the ankle and trunk while decreasing the power absorption at the knee and hip. The decreased knee and hip joint power during squats with knee excursion may be the result of decreased quadriceps activation (Padua et al., 2012; Slater and Hart, in press), causing an increase in joint power production at the trunk. This trade-off between knee and trunk joint power is particularly evident during the anterior maligned squat; as knee joint power decreases, trunk joint power increases (Fig. 5). Although these changes in power distribution are small, the difference in maligned and control squat trunk power had very large effect sizes (Figs. 6 and 7). This supports that the change in distribution of joint power alters the nature of the squat from a primarily quadriceps dominant exercise (Isear et al., 1997; Escamilla et al., 1998; Caterisano et al., 2002; Dionisio et al., 2008) to increased trunk contribution to execute the movement (Escamilla et al., 2001; Dionisio et al., 2008).

Sports medicine professionals may need to consider the potential for excessive loading on the knee joint with knee excursion in the sagittal or frontal plane. The increased internal knee extension moment coupled with increased knee joint power generation near peak knee flexion with anterior knee excursion may lead to increased patellofemoral contact forces (Mesfar and Shirazi-Adl, 2005; Shalhoub and Malatsky, 2014; van den Tillaar et al., 2014). Patellofemoral forces are highest around 90–100 degrees of knee flexion (Escamilla et al., 2009a; Fekteke et al., 2014), when hip and trunk power decreased while ankle and knee power increased in the anterior maligned squat compared to the control squat. These kinetic changes are similar to those seen in individuals with patellofemoral pain syndrome with abnormal patellar tracking (Powers, 1999; Fulkerson, 2002). Furthermore, increased Q-angle has been associated with a more laterally shifted patella resulting in increased contact forces during knee flexion (Huberti and Hayes, 1984; Mizuno et al., 2001), which suggests that frontal plane malalignments increases contact forces at the knee. Although restricting anterior displacement may increase forces at the trunk, the results of this study suggest that sagittal plane malalignment during closed chain exercise may also increase knee contact forces (Mesfar and Shirazi-Adl, 2005; Trepczynski et al., 2012; Shalhoub and Malatsky, 2014). Furthermore, commonly observed technique deviations in a common exercise may lead to persistent altered loading of the ankle and knee. Persistent altered loading patterns during squatting may result in similar cartilaginous degeneration (Lee et al., 2001) seen with altered gait kinematics in people with osteoarthritis (Andriacchi et al., 2009). Future research should continue to explore the consequences of anterior knee excursion in order to establish safe guidelines for anterior knee displacement during squatting.

Some limitations were present in the current study. The subjects in this study purposefully collapsed their knees medially and anteriorly while squatting, however the findings in this study agree with previous researchers who have noted increased ankle contribution during passive medial knee displacement (Padua et al., 2012). Knee flexion angle and squat velocity were also not standardized in the current study, however all participants received the same instructions which best simulates the way the squat would be taught in a clinic or gym (Czaprowski et al., 2012). Furthermore, subjects likely used the same timing for each squat. Although squat velocity was not standardized, the descending and ascending phases of the squat were reduced to 50 points to standardize the squat cycle based on kinematic events. Center of pressure was also not reported in the current study. Changes in center of pressure, such as anterior displacement during anterior maligned squats, would result in an increased moment arm and torque at the ankle joint. Future research regarding lower extremity alignment during the squat should consider changes in center of pressure to better interpret changes in joint torques.

5. Conclusion

The results of the study support that excessive knee excursion in the frontal and sagittal planes alters joint moments, power absorption, and power generation in the lower extremity and trunk. The increased ankle and trunk joint power during malaligned squatting indicates that increased sagittal and frontal plane knee excursion during squats may change the nature of the exercise from a predominantly knee and hip strengthening exercise to distal and proximal contribution to execute the movement. Sports medicine professionals using the bilateral squat for quadriceps strengthening must consider knee alignment to reduce ankle and trunk involvement during the movement.

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Conflict of interest

The authors declare that they have no conflict of interest.

References
