Original article

Patellar tendon stress between two variations of the forward step lunge

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Abstract

Background: Patellar tendinopathy (PT) or "jumper's knee" is generally found in active populations that perform jumping activities. Graded exposure of patellar tendon stress through functional exercise has been demonstrated to be effective for the treatment of PT. However, no studies have compared how anterior knee displacement variations during the commonly performed forward step lunge (FSL) affect patellar tendon stress.

Methods: Twenty-five subjects (age: 22.69 ± 0.74 years; height: 169.39 ± 6.44 cm; mass: 61.55 ± 9.74 kg) performed 2 variations of an FSL with the anterior knee motion going in front of the toes (FSL-FT) and the knee remaining behind the toes (FSL-BT). Kinematic and kinetic data were used with an inverse-dynamics based static optimization technique to estimate individual muscle forces to determine patellar tendon stress during both lunge techniques. A repeated measures multivariate analysis was used to analyze these data.

Results: The peak patellar tendon stress, stress impulse, quadriceps force, knee moment, knee flexion, and ankle dorsiflexion angle were significantly greater ($p < 0.001$) during the FSL-FT as compared to the FSL-BT. The peak patellar tendon stress rate did not differ between the FSL-FT and FSL-BT.

Conclusion: The use of an FSL-FT as compared to an FSL-BT increased the load and stress on the patellar tendon. Because a graded exposure of patellar tendon loading with other closed kinetic chain exercises has proven to be effective in treating PT, consideration for the prescription of variations of the FSL and further clinical evaluation of this exercise is warranted in individuals with PT.

1. Introduction

Patellar tendinopathy (PT) or "jumper's knee" is generally found in active populations that perform jumping activities as demonstrated by the increased prevalence in volleyball (31.9%) and basketball (44.6%) athletes.[1] Raising and lowering exercises like squats, lunges, and heel raising and lowering exercises have been shown to be effective in treating lower extremity tendinopathies, and these exercises are often described as eccentric strength training even though they both use concentric and eccentric muscle activation.[2–6] However, the reasons for eccentric loading regimen effectiveness are largely unknown.[3,7] Different neuromuscular changes could be responsible for the eccentric exercise benefits in rehabilitation.[7] Despite the forward step lunge (FSL) being a commonly used exercise in lower extremity strength and rehabilitation programs[8] due to dynamic balance demands,[9] manipulation of lower extremity kinematics to increase patellar tendon stress,[10] and an eccentric lowering phase that involves all 4 quadriceps muscles,[11] it is rarely included in rehabilitation protocols for patients with PT.[12,13] Rather few investigations have focused on the FSL compared to the squat. Physical therapists often use different kinds of squat techniques during rehabilitation programs.[14–17] Most of the previous literature regarding PT rehabilitation exercises has focused on the squat on a decline board,[14,16–18] which is hypothesized to increase patellar tendon stress by increasing the knee extension moment on a decline board. Longpré et al.[19] reported greater quadriceps muscle activation and a higher internal knee extension moments during lunging *vs.* squatting. It seems that the use of the lunge and a variation in technique may serve to increase patellar tendon stress through functional exercise during rehabilitation.

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There are different techniques for lunges, including variations in step length,[10] walking or jumping lunges,[11] or different trunk positions.[20] Keeping the knee behind the toes is a common cue during performing a proper form of squat and lunges.[21,22] The amount of anterior knee motion relative to the foot has shown to affect quadriceps forces during an FSL, which may allow for increased stress on the patellar tendon. Escamilla et al.[10] reported an increase of up to 30% in quadriceps forces, estimated by electromyography, during short FSL as compared to a long FSL and concluded that the patellofemoral joint force and stress are smaller during long FSL compared to short FSL. However, by manipulating step length in the lunge they effectively altered knee flexion angle, but not necessarily where the knee was in relationship to the foot.

It is yet unknown how manipulating FSL by either keeping the knee over the foot and behind the toes *vs.* keeping the knee over the foot but allowing the knee to move in front of the toes in the sagittal plane with standardized step length may affect patellar tendon stress. Thus, the aim of our study was to provide a comparison of patellar tendon stress during 2 variations of the FSL exercise: with the knee translated in front of the toes (FSL-FT) and with the knee translated behind the toes (FSL-BT). Changes in shank position and knee-joint flexion will alter the direction of the ground reaction force vector and the moment arms. These variables may influence knee-joint loading. Therefore, we hypothesized that there will be an increased patellar tendon stress with FSL-FT due to the increased anterior motion of the knee and resultant increased knee-flexion angle and quadriceps force.

2. Materials and methods

2.1. Subjects

Twenty-five healthy female subjects (age: 22.69 ± 0.74 years; height: 169.39 ± 6.44 cm; mass: 61.55 ± 9.74 kg) participated in this study. The inclusion criteria included a score of 4 or greater on the Tegner activity scale[23] and no report of pain or knee symptoms associated with patellofemoral pain syndrome or PT that had limited their functional or recreational activity in the past 12 months. Participants with a traumatic knee injury in the past 6 months on either knee, a surgery on either lower extremity in the past 12 months, history of cardiovascular pathology, or currently pregnant were excluded. Informed consent was given by all participants regarding the testing protocol as approved by the Institutional Review Board at the University of Wisconsin–La Crosse.

2.2. Protocol

All participants were fitted with the same type of footwear (Model 629; New Balance, Boston, MA, USA) and completed a 5-min active warm-up by walking at a self-selected pace on a treadmill. Because the criteria for lunge step length varied in the literature,[8,10,20,24–26] 100% of the leg length of the subject (apex of greater trochanter to apex of lateral malleolus on the right leg) was used to standardize the step length for both FSL techniques.

A metronome, set at 0.5 Hz, was used to standardize a 2-s descending phase and a 2-s ascending phase. The right leg was
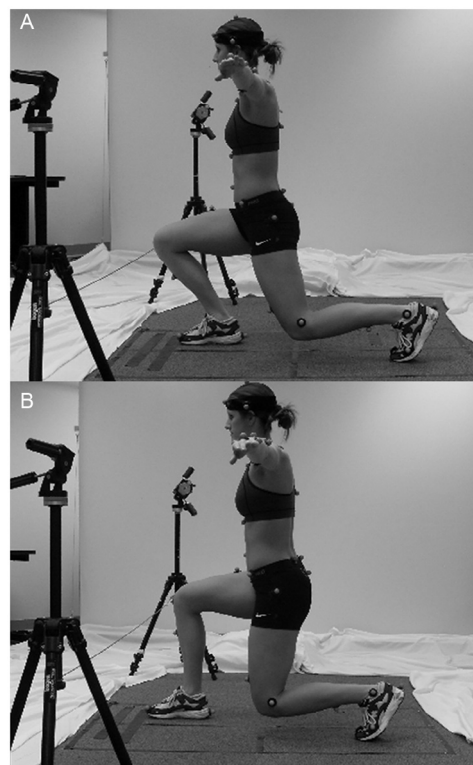

Fig. 1. (A) Forward step lunge with knee in front of toes (FSL-FT) and, (B) Forward step lunge with knee behind toes (FSL-BT).

the lead leg for all participants. Prior to each trial, a demonstration and verbal explanation was provided by the same researcher for each participant. The order of the 2 FSL techniques was randomly determined through a coin flip. For both FSL techniques, the subjects were cued to maintain an erect trunk posture while maintaining their arms abducted at 90° with their elbows fully extended. We controlled trunk position as this has been shown to influence kinematics, kinetics, and muscle activity during forward lunge.[19] We instructed each participant to "remain upright throughout each trial" in order to better examine the effect of anterior knee translation on patellar tendon stress. Lead-leg foot contact occurred just prior to a step marker that was placed at 100% of the step length. The lead-leg foot placement and contact position was constrained to a heel strike to foot flat position while executing the lunge. The knee of the lead leg made contact with a guide cord that was placed at the level of the participants' knee to ensure proper anterior knee movement for the respected FSL technique. Thus, the major difference between the 2 FSL techniques was the placement of the guide cord. For the FSL-FT, the guide cord was placed at 110% of the step length in order to result in knee motion past the participants' toes (Fig. 1A). For the FSL-BT, the guide cord was placed directly over the step marker (100% of leg length) such that anterior knee motion did not go past the participants' toes (Fig. 1B). Each subject performed 5 consecutive repetitions for each FSL technique. The trials were repeated if the subject demonstrated an inability to maintain temporal standardization during either the descending or ascending

phases, improper anterior knee motion during the descending phase, or an inability perform the lunge with the correct step length.

2.3. Instrumentation

Forty-seven reflective markers were placed on the body at the head, trunk, pelvis, and bilateral upper and lower extremities.[27] Head markers were placed on the right, left, top, and front. Trunk markers were placed on C7 and T10 spinous processes, navel, xiphoid process, sternal notch, and on the right scapula. Bilateral upper extremity markers were placed at the acromion process; near the deltoid insertion; medial and lateral humeral epicondyles; the forearm; at the ulnar and radial styloid processes; and at the second metacarpophalangeal joint. Markers defining the pelvis were placed at bilateral anterior superior and posterior superior iliac spines along with 1 marker being placed at the apex of the sacrum. Lower extremity markers were placed bilaterally on the greater trochanter, anterior thigh, lateral femoral epicondyle, anterior tibia, and lateral malleolus. The foot segment consisted of 3 markers placed on the shoe at the heel, the great toe, and the fifth metacarpophalangeal joint. All markers were left in place during data collection. Fifteen cameras (Motion Analysis Corp., Santa Rosa, CA, USA) were used to collect motion analysis data at 180 Hz. Synchronized analog data were collected at 1800 Hz with the use of 4 force platforms (Model 4080; Bertec Corp., Columbus, OH, USA).

2.4. Data processing

Raw kinematic and analog data were filtered with a second order Butterworth low-pass filter using an 8 Hz cutoff frequency. Joint angles, kinetic data, and muscle forces were processed using Human Body Model (Motek Medical, Amsterdam, the Netherlands). Muscle forces were calculated based on a 44-degree of freedom (DOF) musculoskeletal model with 16 rigid segments.[27] The head relative to the pelvis was modeled with 3-DOF. The trunk was modeled as 3 segments with 3-DOF, upper arm with 6-DOF, elbow with 2-DOF, and wrist with 2-DOF. The pelvis segment had 6-DOF and was able to rotate and translate in all 3 dimensions with respect to the ground. The knee was modeled as a 1-DOF hinge joint and the ankle joint was modeled with 2-DOF, respectively. The inertial characteristics of the segments used in the model were based on participants' total body mass and segment lengths.[28] Overall, 300 muscle tendon units were represented in the model in which muscle parameters such as muscle insertion and wrapping points were determined as in Delp et al.[29]

Muscle forces were estimated from the joint moments by minimizing a static cost function where the sum of squared muscle activations was related to maximum muscle strengths at each time step of the model.[30] The static optimization problem was solved using a recurrent neural network.[31] The muscle forces and joint moments were normalized by weight.

The muscle forces from the Human Body Model were then used to quantify the total patellar tendon force by summing the muscle forces of the rectus femoris, vastus medialis, vastus lateralis, and vastus intermedius throughout each repetition. The patellar tendon stress was calculated by dividing the patellar tendon force by the cross-sectional area. The patellar tendon cross-sectional area was determined from Hansen et al.[32] and applied to all participants. Stress rate was then determined from the instantaneous slope of the stress vs. the time curve. Stress impulse was determined based on the integrated stress time curve during each lunge repetition.

2.5. Statistical analysis

Sample size was calculated a priori using $\beta = 0.20$ and $\alpha = 0.05$. A minimum sample size of 6 was determined based on peak patellar-tendon force from Frohm et al.[14] A multivariate analysis of variance with repeated measures was performed using an $\alpha = 0.05$. Follow-up univariate tests were then performed to detect differences between the 2 types of lunge techniques for each variable. Statistical calculations were completed in SPSS Version 22.0 (IBM Corp., Armonk, NY, USA) software.

3. Results

Multivariate analysis indicated there were differences in kinetic (Wilks $\lambda = 0.071$, $p < 0.001$) and kinematic (Wilks $\lambda = 0.007$, $p < 0.001$) variables between the FSL-FT and FSL-BT lunge techniques. The peak patellar tendon stress was 11.1% greater during the FSL-FT than the FSL-BT (Table 1). No difference was found between the 2 FSL techniques for peak

Table 1
Kinetic and kinematic variables for the forward step lunge behind the toes (FSL-BT) and forward step lung in front of toes (FSL-FT) techniques (mean ± SD).

|	FSL-BT	FSL-FT	Mean difference	p
Peak patellar tendon stress (MPa)	0.18 ± 0.02	0.20 ± 0.02	−0.02	<0.001
Peak patellar tendon stress rate (MPa)	1.17 ± 0.40	1.17 ± 0.36	0	0.986
Peak patellar tendon stress impulse (MPa·s)	0.0016 ± 0.0002	0.0019 ± 0.0003	−0.0003	<0.001
Peak quadriceps force (BW)	6.79 ± 0.64	7.76 ± 0.88	−0.97	<0.001
Peak knee extension moment (BW·m)	−0.155 ± 0.004	−0.209 ± 0.006	0.054	<0.001
Peak hip extension moment (BW·m)	−0.109 ± 0.026	−0.091 ± 0.019	−0.018	<0.001
Peak ankle plantar flexion moment (BW·m)	0.023 ± 0.009	0.057 ± 0.009	−0.034	<0.001
Peak hip flexion angle (°)	100.0 ± 9.9	89.0 ± 10.3	11.0	<0.001
Peak trunk flexion angle (°)	3.5 ± 10.2	3.2 ± 9.6	0.3	0.595
Peak knee flexion angle (°)	110.2 ± 4.9	124.7 ± 7.4	−14.5	<0.001
Peak ankle dorsiflexion angle (°)	19.5 ± 4.5	46.7 ± 4.7	−27.2	<0.001
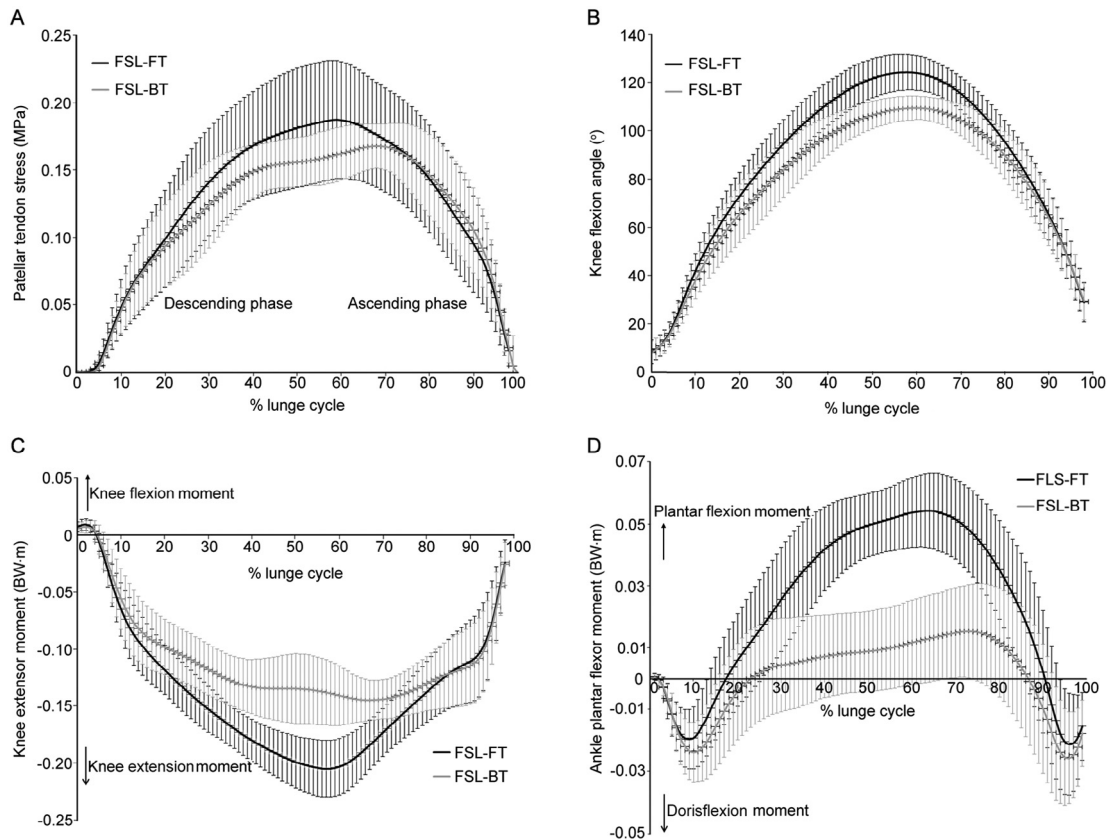
Fig. 2. Ensemble average and standard deviation time series graphs of the forward step lunge (FSL) (mean ± SD). (A) Patellar tendon stress; (B) knee flexion angle; (C) knee extension moment; and (D) ankle plantar flexion moment. FSL-BT = forward step lunge with knee behind toes; FSL-FT = forward step lunge with knee in front of toes.

patellar tendon stress rate. Patellar tendon stress impulse was 18.8% greater during the FSL-FT as compared to the FSL-BT.

Fig. 2 illustrates the patellar tendon stress, knee flexion angle, knee extension moment, and ankle plantar flexion moment during FSL-BT and FSL-FT. Fig. 2A shows that there was a similar trend for the mean patellar tendon stress during both FSL techniques, although the peak stress occurs at about 60% during FSL-FT and about 75% during FSL-BT. With respect to patellar tendon stress (Fig. 2A) and knee flexion angle (Fig. 2B), during the descending phase (0–50% FSL), there was a progressive increase in patellar tendon stress, and during the ascending phase (50%–100% FSL) there was a progressive decrease in patellar tendon stress. In addition, the mean patellar tendon stress was 25.4% greater during the FSL-FT and 38.5% greater during the FSL-BT at the midpoint of the ascending phase (75% FSL) as compared to the descending phase (25% FSL). Fig. 2C depicts the knee extension moment, which reaches a peak at about 58% during FSL-FT and 70% during FSL-BT. Fig. 2D depicts the ankle plantar flexion moment, which peaks at about 65% during FSL-FT and 78% during FSL-BT. FSL-FT has a larger knee extension and ankle plantar flexion moment overall. These peak knee extension and ankle plantar flexion moments for both tasks occurred during the ascending phase but slightly later during the FSL-BT. These peak moments occurred earlier with the FSL-FT with similar timing as the peak patellar tendon stress.

The peak quadriceps forces and knee moment had a greater magnitude, 12.6% and 25.8%, respectively, for the FSL-FT compared to the FSL-BT (Table 1). Likewise, peak hip flexion moment (16.5%) and knee flexion angle (13.2%) were greater during the FSL-FT as compared to the FSL-BT (Table 1). Peak hip flexion angle was 11.0% greater during the FSL-BT condition. There was no difference found between trunk flexion angles during the 2 FSL techniques. Peak knee flexion angle, peak ankle dorsiflexion angle, and peak ankle plantar flexion moment were 11.6%, 58.2%, and 59.6%, respectively, greater during the FSL-FT than the FSL-BT (Table 1).

4. Discussion

The primary purpose of this investigation was to determine how alterations in sagittal anterior knee motion during an FSL affect patellar tendon stress. The study findings support our hypotheses that the performance of a lunge with the knee translating beyond the toes, as demonstrated by the FSL-FT, resulted in greater peak patellar tendon stress and patellar tendon stress impulse, while FSL-FT displayed higher knee and ankle flexion angles with less hip flexion angle, higher knee extension moment, plantar flexion moment, and less hip extensor moment compared to FSL-BT. These findings could play a role in the formulation of future regimes utilized for the treatment of individuals with PT.

The effects of a higher mechanical load in symptomatic tendons of individuals suffering from lower extremity

tendinopathies have been well documented in the literature, with findings of decreased neovascularization[4] and tendon hypertrophy,[5,15] as well as increased blood circulation.[33] The present data showed the peak patellar tendon stress and stress impulse were, respectively, 11.1% and 18.8% greater during the FSL-FT than the FSL-BT. The increased patellar tendon stress during the FSL-FT appears to provide greater patellar tendon loading and therefore may result in superior patellar tendon structural adaptations and improvements as compared to FSL-BT exercise with individuals with PT. The manipulation of performing an FSL-BT may also serve as a progression to the FSL-FT during rehabilitation.

Numerous studies have reported that a linear relationship exists between knee flexion angle and quadriceps force during closed kinetic chain functional movements.[14,34–36] In the present study, a similar relationship was identified as there was both a greater peak knee flexion angle and peak quadriceps force during the FSL-FT as compared to FSL-BT. Escamilla et al.[10] performed a comparable study depicting changes in patellofemoral joint stress during step length variations in the FSL. They reported an even larger increase in quadriceps force (20%–30%) during lunges with increased knee flexion angle as compared to our study (12.6%), which appears due to our standardized step length. Stress is force per area, so the increase in quadriceps force during the FSL-FT appears to be a main contributing factor in the greater patellar tendon stress. Because the FSL is considered to be a closed kinetic chain exercise, ankle, and hip flexion angle are increased and decreased, respectively, during FSL-FT. Not only joint angles are different, but also hip, knee, and ankle joint moments are different. Fig. 2C and Fig. 2D depicted the knee extension and ankle plantar flexion moment, which is greater during FSL-FT. This difference is expected due to the more anterior location of the body center mass from the ankle during FSL-FT. This highlights the difference in the location of the ground reaction force vector between movements and how it seems to influence the moment arms relative to each joint. With a higher knee extension, plantar flexion moment, and lesser hip extensor moment during FSL-FT of the lead leg, higher stress occurs in the patellar tendon.

There were differences in peak patellar tendon stress and impulse between the 2 FSL techniques but no difference between peak patellar tendon stress rate (Table 1). Although we controlled time by standardizing the 2-s descending and ascending phase during the motions, FSL-FT demonstrated higher knee and ankle displacement rather than FSL-BT. Fig. 2A showed the patellar tendon stress where the peak stress occurs at about 60% during FSL-FT and 75% FSL-BT. The peak knee extension and plantar flexion occur later in the movement as well for the FSL-BT. In combination, these may affect the timing differences in peak patellar tendon stress. The peak patellar tendon stress curve slope looks similar until 20% and after 70% of motion (about 50% of total lunge motion). But the peak knee flexion occurs at about 60% of the squat for both techniques (Fig. 2B). These in combination indicated that the FSL-FT used a more rapid knee extension velocity on average as the overall rate of the exercises was controlled. With the similar rate of movement performed, the FSL-FT requires the

greater knee and ankle motion, which increases the quadriceps force and therefore increases the patellar tendon stress. Even though the timing was largely controlled by using of the metronome, it is plausible that these increases in joint loading are influenced by both different knee positions and different movement dynamics requiring greater muscle force in the lead leg.

While the mechanical loading of the patellar tendon has been shown to be effective for the treatment of PT,[3,15,16] it is also important to note that increased rates of loading have been found to place soft tissue, such as tendons, at risk for injury.[37,38] Therefore, rehabilitation programs incorporating either the FSL-BT or FSL-FT may consider a graded increase in loading rate as performance of these movements at a faster cadence would likely increase these loading rates. There were differences between stress impulses during the FSL techniques whereas the FSL-FT showed a higher impulse. Fig. 2A shows the area under patellar tendon stress curve was higher during FSL-FT than FSL-BT.

Fig. 2A represented patellar tendon stress during entire lunge motion, which included descending and ascending phase. Taken together with knee flexion angle (Fig. 2B), the peak patellar tendon stress appears to occur during the ascending phase. Jönhagen et al.,[11] supported the description of phases when they reported rectus femoris eccentric contraction after 54% of step and jump lunges. These findings may have been the result of a greater quadriceps force requirement needed to accelerate the center of mass during the ascending phase as opposed to the decelerating of the center of mass during the descending phase. Our musculoskeletal model that uses static optimization accounts for the dynamics of the lunge activity and the force production of muscle that span more than a single joint like the quadriceps. Other studies analyzing closed kinetic chain exercises with the same resistance applied throughout the entire repetition have supported this notion as they have reported greater quadriceps activity during the ascending phase rather than the descending phase of this movement.[39–43] Meanwhile, some studies indicate that there may be a neuromuscular inhibition associated with maximum quadriceps contraction during the descending phase of these exercises.[44,45]

In this study, we controlled trunk flexion because the manipulation of trunk position has been shown to alter patellar tendon stress.[20] Our findings show no difference between peak trunk flexion angles during either FSL technique. Farrokhi et al.[20] reported a 19.2% increase in knee extension impulse with lunges where the trunk was in more extension as compared to when flexed. These authors hypothesized that this occurred due to an increase in the knee extension moment due to the posterior location of the body center mass from the knee. This same concept has been applied to the prescription of declined squats for PT. Studies have shown that declined squat had greater knee flexion coupled with a more erect trunk position as compared to the traditional squat on a horizontal surface.[14,18] Therefore, these changes in the sagittal trunk position during an FSL-FT may allow for the ability to further manipulate the amount of patellar tendon stress based on the tissue irritability and the rehabilitation stage of an individual with PT.

There are some limitations that should be considered. Only female subjects participated and therefore further investigations

using male subjects may be warranted. In addition, static optimization was utilized to estimate the muscle forces. Without *in vivo* measurements of muscle force, it is difficult to determine the true accuracy of this technique. Our musculoskeletal model uses 1 degree of freedom for the knee joint, which may affect muscle force estimation and therefore may overestimate patellar tendon load. Lastly, a reference[32] was utilized for determining the patellar tendon cross-sectional areas instead of a direct measurement, which may have affected the resultant peak patellar tendon stress. Many of these limitations, although important, may not influence the overall conclusions of our study because we utilized a repeated measures design where all model parameters and assumptions were systematically applied to all subjects performing both lunge techniques.

5. Conclusion

Our data demonstrate that the patellar tendon stress, stress impulse, quadriceps force, knee extension moment, ankle plantar flexion, and knee flexion angle are higher during FSL-FT than in FSL-BT. Therefore, the patellar tendon undergoes greater loading during the FSL-FT compared to the FSL-BT. Because the squat is performed commonly during PT rehabilitation, further research appears warranted wherein decline squats and the FSL-FT could be examined for their effectiveness in providing patellar tendon stress as well as with rehabilitation outcomes of individuals with PT.

Acknowledgment

Authors' contributions

TWK was involved in the design of the study and project conception, data collection, data processing and performed statistical analysis; NG was involved in the design of the study and project conception, data collection, data processing and performed statistical analysis, and data interpretation and drafting the original manuscript; MZ was involved in data collection, data processing and analysis, performed statistical analysis, and data interpretation and drafting the original manuscript; JH was involved in data collection, data processing and analysis; MT were involved in data interpretation and drafting the original manuscript. All authors have read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

Competing interests

The authors declare that they have no competing interests.

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