The etiology of patellar tendinopathy (jumper’s knee) has been attributed to a significant increase in patellar tendon torques associated with jumping. While some investigators have suggested that patellar tendon torques are greater during takeoff, little is known about the relative magnitudes of patellar tendon torques during takeoff and landing. We hypothesized that peak patellar tendon torques are greater in jump takeoff than in landing, and that there is a linear correlation between jump height and peak patellar tendon torque. Seven asymptomatic, recreational male athletes each performed a series of 21 jumps ranging from low to maximal height. A calibrated fiber-optic sensor, implanted transversely within the patellar tendon was used to measure the knee torque during takeoff and landing. There was no significant difference in the peak patellar tendon torque experienced during takeoff and landing within individuals. There was a moderate correlation \((r = .64)\) between maximum takeoff patellar tendon torques and jump height. There was a weak correlation \((r = .52)\) between maximum landing patellar tendon torques and jump height. There was a moderate correlation \((r = .67)\) between maximum 60°/s isokinetic extension torque and maximum jump height. The lack of a strong correlation between jump height and patellar tendon forces during takeoff or landing suggests that these forces may be technique dependent. Therefore, modifying takeoff and/or landing techniques could reduce patellar tendon force and potentially lessen the incidence of patellar tendinopathy.

**Keywords:** patellar tendon forces, tendinopathy, jump takeoff, jump landing

Patellar tendinopathy, also known as jumper’s knee, is a common injury in jump-intensive sports such as volleyball and basketball (Lian et al., 2005; Ferretti et al., 1983). A recent study has shown that the incidence of jumper’s knee in males is 44.6% for volleyball and 31.9% for basketball players (Lian et al., 2005). Although patellar tendinopathy constitutes a significant problem in a wide variety of sports (Khan et al., 2005), the precise etiopathogenesis of this condition is still a matter of speculation. While most investigators agree that patellar tendinopathy is likely a result of excessive loading of the extensor apparatus during jumping (Lian et al., 1996), the precise magnitude and origin of this excessive force has not been determined.

Studies evaluating elite volleyball players with jumper’s knee have demonstrated that these players have better jumping ability and power generation than players who do not report problems with their tendons (Lian et al., 1996, 2003). These studies have also shown a correlation between knee tendinopathy and jump height in these elite players. These findings have led the authors to conclude that the risk of jumper’s knee may be related to the magnitude of load placed on the extensor apparatus during jumping (Lian et al., 1996). Although these authors have hypothesized that players who jump higher generate more patellar tendon force, they acknowledge that it is unclear whether patellar tendon forces are greater during takeoff or landing (Lian et al., 1996).
Only a few studies have directly measured in vivo patellar tendon forces during human movement (Komi & Ishikawa, 2007; Ishikawa et al., 2003). Finni et al. (2000) have developed a fiber-optic technique that has been used to measure patellar and Achilles tendon forces during various activities, including walking, running, cycling, and jumping. However, in previous studies (Komi & Ishikawa, 2007; Finni et al., 2000) in which direct patellar tendon forces were measured during jumping, the subjects were attached to a sledge to control the joint angle positions and, thus, may not have been allowed total freedom of movement. While the maximum takeoff patellar tendon force in one of the studies (Finni et al., 2000) was calculated to be approximately 7000 N, the constrained tendon force in the other study (Komi & Ishikawa, 2007; Finni et al., 2000) in which direct patellar tendon forces were measured during jumping, the subjects were allowed to test conditions may have affected these results. Therefore, measurements collected during natural, unconstrained jumping and landing may more accurately reflect the magnitudes and patterns of patellar tendon forces occurring during these activities.

The objective of the current study was to compare the maximum patellar tendon torques experienced during jump takeoff and landing. Patellar tendon torque is defined as the torque generated about the center of rotation of the knee by the force in the patellar tendon. Based on the previous work of Lian et al. (1996), we hypothesized that patellar tendon torques experienced during takeoff would be significantly greater than that experienced during landing. We also hypothesized that there would be a linear correlation between jump height and peak patellar tendon torque.

**Methods**

Seven male recreational athletes (age: 25.1 ± 3.4 years, height: 180.9 ± 2.8 cm, weight: 83.1 ± 11.8 kg), participated in this study. All subjects reported no history of orthopedic injury and signed an informed consent form approved by the University of Stellenbosch before participating in the study.

Before implantation, each subject's static maximal jump height was measured by instructing them to perform a single maximal jump. This jump was assessed to be high, medium, or low if it was, respectively, greater than 40 cm, between 40 and 30 cm, or less than 30 cm above the subject's static reach height. The subject was then instructed to jump and touch, by hand, successively increasing height markers. The starting marker was at 42 cm (for the high jumpers), 30 cm (for medium jumpers), or 25 cm (for the low jumpers) above the static reach height of the subject. The height was then increased in 2.5-cm increments until the subject was no longer able to touch the marker. Maximum jump height for each subject, in the context of this study, is defined as the total distance from the floor to the highest marker touched by each subject.

The surgical implantation of the plastic fiber-optic sensor is similar to the procedure described by Finni et al. (2000). With the subject lying supine, the right knee was held at 120° of flexion. Under local anesthetic, a board-certified sports medicine physician inserted a 19 gauge spinal needle through the cross-section of the patellar tendon in a lateral-to-medial direction using ultrasonic guidance. A sterile 0.5-mm plastic fiber sensor (PGR500; Toray Industries, Tokyo, Japan) was inserted into the distal opening of the needle and the needle was then removed, leaving the fiber-optic sensor in place within the tendon. The fiber optic sensor was then connected to a custom-made transceiver (Dillon et al., 2007). None of the subjects experienced any discomfort during or after the implantation.

Following implantation of the fiber-optic sensor, each subject was allowed to perform a self-selected warm-up. The subject's maximum right leg power output was then measured in flexion and extension using an open-chain isokinetic machine (Biodex Medical Systems, Shirley, NY). Each subject performed five maximal effort repetitions at three isokinetic rates (60°/s, 150°/s, and 300°/s). These isokinetic tests were then used to calibrate the fiber-optic sensor.

The optical fiber was calibrated following a procedure described by Finni et al. (2000) using the isokinetic knee flexion test. The data streams were synchronized during the analysis by identifying the starting and maximum torque values in both data sets (Figure 1). These were then used to calibrate the optical fiber for all three isokinetic speeds (i.e., six points for each speed, giving a total of 18 calibration points for each subject). The linear correlation between applied torque and patellar tendon torque was strong (r > .93) and significant (p < .01) for all subjects.

Previous work by Elvin et al. (2007a) has shown that maximum landing ground reaction force is not correlated to jump height. Thus, it is important to test landing from various heights. Each subject performed a sequence of jumps starting with a medium height jump (defined as 95% of the maximum height jump as measured before sensor implantation), followed by a low jump (defined as 90% of maximum jump height), and finishing with a maximum height jump (100% of maximum jump height). This sequence was repeated seven times, for a total of 21 jumps per subject. Three adjustable height markers were used to indicate the predetermined jump heights. The subjects were bare-footed throughout the test and the rest time between jumps was self-selected by the subject. To permit the most natural movements, subjects were not given any instruction on jumping or landing technique except to take off from a standing position and to land on both feet (Figure 2).

During each jump, vertical and sagittal accelerations were measured wirelessly using a custom-built accelerometer sensor system (ZeroPoint Technology, Johannesburg, South Africa). The two-axis accelerometer system was mounted approximately 3 cm superior to the right anterior superior iliac spine. The accelerometer system was affixed to a tight fitting adjustable elastic band that was secured around the subject's pelvis. Athletic tape was used to secure further the accelerometer system to the subject's skin. The accelerometer system...
were used to find the subject’s maximum patellar tendon takeoff and landing torques. Only the maximum patellar tendon torque at takeoff (PTTO) and landing (PTL) from each subject were considered in the data analysis. Since subjects were not matched for quadriceps strength, jumping technique, or weight, each subject’s maximum landing patellar tendon torque was normalized using their own maximum takeoff patellar torque, that is, PTL/PTTO. This normalization reduces any error associated with calibration. Thus, a normalized patellar tendon torque of greater than one indicates that the landing torque is greater than the takeoff torque. Using a two-tailed \( t \) test, a 0.05 level of type I error was considered statistically significant. All results are reported as mean and standard deviation.

The ratio of the peak tendon torque during jump landing and takeoff for each of the 21 jumps performed by every subject was calculated. The peak takeoff and landing patellar tendon torques were extracted for each jump (Figure 2). For each subject, the 21 peak takeoff and landing measurements were used to find the subject’s maximum patellar tendon takeoff and landing torques.

Only the maximum patellar tendon torque at takeoff (PT\(_{TO}\)) and landing (PT\(_{L}\)) from each subject were considered in the data analysis. Since subjects were not matched for quadriceps strength, jumping technique, or weight, each subject’s maximum landing patellar tendon torque was normalized using their own maximum takeoff patellar torque, that is, PT\(_{L}/PT_{TO}\). This normalization reduces any error associated with calibration. Thus, a normalized patellar tendon torque of greater than one indicates that the landing torque is greater than the takeoff torque. Using a two-tailed \( t \) test, a 0.05 level of type I error was considered statistically significant. All results are reported as mean and standard deviation.

The ratio of the peak tendon torque during jump landing and takeoff for each of the 21 jumps performed by every subject was calculated. The means and standard deviations of this intrajump ratio for each subject was compared with their PT\(_{L}/PT_{TO}\) ratio using a two-tailed \( t \) test; a 0.05 level of type I error was considered statistically significant.

Figure 1 — Maximum effort knee flexion-extension torque measured by the isokinetic testing machine (upper graph) and optical fiber transducer output (lower graph) at a speed of 60°/s. The six marked points (together with 12 other points from faster speed isokinetic tests) are used for optical fiber calibration. The fiber output is measured in volts.
Figure 2 — Schematic depiction of experimental layout, patellar tendon torque, and vertical acceleration. Marker heights are set at 95%, 90%, and 100% of subject’s maximum jump height. The bottom graphs represent typical patellar tendon torque and vertical acceleration measurements for a single jump. Flight time is defined as the time between the first and last zero vertical acceleration crossing between the takeoff and landing peaks.
Patellar tendon torque was also normalized by the subject’s height and weight. For each subject, linear least square fitting was used to analyze the relationship between (a) jump height and normalized patellar tendon takeoff torque and (b) jump height and normalized patellar tendon landing torque. For all subjects, a linear least square fit was also used to analyze the relationship between maximal 60°/s isokinetic knee flexion torque and maximal jump height. The significance of the correlation coefficient was assessed using a 0.05 level for type I error.

Results

The maximum jump heights for the subjects ranged from 35 cm to 58 cm (mean 43.3 cm, standard deviation 8.1 cm). The normalized maximum landing patellar torque and maximum takeoff patellar tendon torques, $PT_L/PT_{TO}$, in the subjects tested was $0.90 \pm 0.25$ (Figure 3), which was not significant ($\alpha > 0.05$). However, in two of the seven subjects, patellar tendon torque was greater in landing than in takeoff. The intrajump ratio was not significantly different ($\alpha > 0.05$) from the $PT_L/PT_{TO}$ for any of the subjects (Figure 3).

There was a moderate (mean $r = .64$) correlation between the maximum patellar tendon takeoff torque and jump height (Figure 4). This correlation was significant for six of the seven subjects. There was a weak (mean $r = .52$) correlation between the maximum patellar tendon landing torque and jump height (Figure 5). This correlation was significant for five of the seven subjects. There was a moderate ($r = .66$) and significant ($p < .01$) linear correlation between the maximum 60°/s isokinetic flexion torque and maximum jump height.

Discussion

The results of this study demonstrate that for a group of seven young male recreational athletes, there was no significant difference between patellar tendon torque during takeoff and during landing. In two out of the seven subjects, maximum patellar tendon landing torque

![Figure 3](image-url) — The maximum patellar tendon landing torque ($PT_L$) normalized by the maximum patellar tendon takeoff torque ($PT_{TO}$) for the seven subjects. A normalized patellar tendon torque, $PT_L/PT_{TO}$, value greater than 1 indicates that the patellar tendon landing torque is greater than the patellar tendon takeoff torque. The mean and standard deviation for the intrajump ratio of the peak landing to takeoff patellar tendon torques for each subject is indicated by the circles and error bars.
was greater than maximum takeoff torque. Furthermore, there was only a weak correlation between maximum patellar tendon force and maximum jump height both during takeoff and landing. As found in previous studies (Paasuke et al., 2001), there was a moderate correlation between maximum jump height and maximum isokinetic peak knee extension torque.

Previous work (Lian et al., 1996) has suggested that during jumping, the increased muscle force required for takeoff may be a cause of patellar tendinitis. However, the current study suggests that the patellar tendon forces during both landing and takeoff could be important factors when considering the cause of patellar tendinopathy. Furthermore, in the small recreational athletic population examined in this study, patellar tendon torque is only weakly correlated to maximum jump height. Therefore, the hypothesis that individuals with a greater maximum jump height generate greater patellar tendon force (Lian et al., 1996) could not be confirmed or denied. Additional research, in a larger cross-section of athletic abilities, is required to rigorously test this hypothesis. However, because patellar tendinopathy has been shown to affect both recreational and elite athletes (Stasinopoulos & Stasinopoulos, 2004), the current study does provide relevant information for an at-risk group.

It is likely that for the recreational athletes participating in the current study, jump technique could be significantly different from subject to subject. This could explain the lack of correlation between jump height and maximum patellar tendon torque during takeoff. Between 33 and 50% of maximum jump height work is generated by the quadriceps muscles (Luhtanen & Komi, 1978; Fukashiro & Komi, 1987; Hubley & Wells, 1983). Other factors that have been shown to contribute to maximum jump height include muscle contraction velocity...
was no significant difference between (1) the mean intrajump ratio of the peak landing to takeoff patellar tendon torques and (2) the ratio of the maximum landing to takeoff patellar tendon torques. This would indicate that the subject-to-subject variability of the maximum landing to takeoff patellar tendon torques is relatively consistent and is likely a function of each subject's specific jump technique rather than an error in the measurement method.

Previous studies have also shown that incidence of knee tendinopathy in elite beach volleyball athletes is significantly lower than for players who play on hard surfaces (9% for beach volleyball compared with approximately 40% for hard surface players) (Lian et al., 2005). Lian et al. (2005) have hypothesized that jumping and landing patellar tendon forces on soft sand are significantly less than for jumping on hard surfaces. The stiffness of landing from a jump has been shown to directly affect the maximum ground reaction force (i.e., muscle power) (Voigt et al., 1995), tendon stiffness (Bobbert et al., 1986), hip strength (Luhtanen & Komi, 1978; Fukashiro & Komi, 1987; Hubley & Wells, 1983; Vanezis & Lees, 2005), ankle strength (Luhtanen & Komi, 1978; Fukashiro & Komi, 1987; Hubley & Wells, 1983; Lees et al. 2004), arm swing (Vanezis & Lees, 2005; Lees et al., 2004), and jump coordination (Vanezis & Lees, 2005). Jump coordination would also explain the apparent difference between the Lian et al. (1996) results and the current study. The Lian et al. (1996) study used elite volleyball players, for whom it would be expected that jumping coordination is closer to optimal. The stronger correlation between the maximum patellar tendon takeoff torques and jump height observed in the current study might indicate that jump technique is more uniform during takeoff than during landing.

The present study shows a relatively large subject-to-subject variability in maximum landing to takeoff patellar tendon torques. However, for each subject, there was no significant difference between (1) the mean intrajump ratio of the peak landing to takeoff patellar tendon torques and (2) the ratio of the maximum landing to takeoff patellar tendon torques. This would indicate that the subject-to-subject variability of the maximum landing to takeoff patellar tendon torques is relatively consistent and is likely a function of each subject's specific jump technique rather than an error in the measurement method.

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Figure 5 — Least square fit lines (solid) for the maximum patellar tendon torque and jump height for the seven subjects (S1 to S7) during landing. The landing patellar tendon torques (PTL) are normalized by body weight and height (BW × BH). The stars represent that the least square fit is significant (α = .05)
that the computer modeling work of Pflum et al. (2004) showed a landing patellar tendon force of 4500 N, which is similar to the mean landing force of 4000 N measured in the current study. Furthermore, in the current study, the system was calibrated at knee angles that could differ from those used in jump takeoff or landing. This could introduce an error in the measurement because knee extensor moment arms can vary with knee angle, such that the knee torque calibration may not hold as knee angle is varied.

The aforementioned limitations notwithstanding, we believe the current study provides significant information regarding the relative patellar tendon torques experienced during jump takeoff and landing.

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