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Am. J. Sports Med. 2008; 36; 2119 originally published online Jul 1, 2008;
DOI: 10.1177/0363546508319311

The online version of this article can be found at:
http://ajs.sagepub.com/cgi/content/abstract/36/11/2119
Differential Forces Within the Proximal Patellar Tendon as an Explanation for the Characteristic Lesion of Patellar Tendinopathy

An In Vivo Descriptive Experimental Study

Edwin Mark Dillon,*† MD, Pieter J. Erasmus,† MD, Jacobus H. Müller,‡ Cornie Scheffer,‡ and Richard V. P. de Villiers,§ MD

From the †Knee Clinic Stellenbosch, Department of Orthopaedic Surgery, Stellenbosch University, Stellenbosch, South Africa, ‡Biomedical Engineering Research Group, Department of Mechanical and Mechatronic Engineering, Stellenbosch University, Stellenbosch, South Africa, and §Drs. Van Wageningen and Partners, Stellenbosch Medi-Clinic, Stellenbosch, South Africa

**Background:** Patellar tendinopathy is a common condition affecting the posterior region of the proximal patellar tendon, but the reason for this typical location remains unclear.

**Hypothesis:** The posterior region of the proximal patellar tendon is subjected to greater tendinous forces than is the corresponding anterior region.

**Study Design:** Descriptive laboratory study.

**Method:** An optic fiber technique was used to detect forces in both the anterior and the posterior regions of the proximal patellar tendon in 7 healthy persons. The optic fiber force sensor works on the principle of the amplitude modulation of transmitted light when the optic fiber is geometrically altered owing to the forces acting on it. Longitudinal strain in the tendon or ligament produces a negative transverse strain, thus causing a force that effectively squeezes the optic fiber. Measurements were recorded during the following exercises: closed kinetic chain quadriceps contraction (eccentric and concentric), open kinetic chain quadriceps contraction (eccentric and concentric), a step exercise, and a jump exercise.

**Results:** During all the exercises, the peak differential signal output in the posterior location of the proximal patellar tendon was greater than in the corresponding anterior location. The greatest differential signal output was found in the jump and squat exercises.

**Conclusion:** The posterior region of the proximal patellar tendon is subjected to greater tendinous forces than is the corresponding anterior region. This finding supports the tensile-overload theory of patellar tendinopathy.

**Clinical Relevance:** Jump activities and deep squat exercises expose the patellar tendon to very large tendinous forces.

**Keywords:** patella; tendinopathy; tendon forces; optic fiber

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*Address correspondence to Edwin Mark Dillon, MD, Knee Clinic Stellenbosch, Room G3, Stellenbosch Medi-Clinic, Die Boord, Stellenbosch 7600, South Africa (e-mail: dillon@orthoclinic.co.za).

No potential conflict of interest declared.

The American Journal of Sports Medicine, Vol. 36, No. 11 DOI: 10.1177/0363546508319311
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Patellar tendinopathy (PT) was first described by Blazina et al in 1973 as jumper’s knee. It is a common condition affecting the proximal attachment of the patellar tendon to the inferior pole of the patella and is one of the most common forms of chronic tendinopathy. It has, in fact, been shown to have an incidence of up to 20% in an athletic population. The lesion in PT is located within the posterior...
fibers of the proximal patellar tendon. Investigations into the region-specific mechanical properties of the patellar tendon are, however, limited; hence, the reason for this typical location remains unclear.

There appears to be little or no support for an inflammatory origin for PT, as the absence or scarcity of inflammatory cells has been consistently reported. It has also been shown that the levels of the inflammatory mediator PGE2 are not raised in PT. Johnson et al proposed the impingement of the inferior pole of the patella against the patellar tendon as the cause of PT, but recent studies have disputed this. It is accepted, however, that the long inferior pole of the patella sometimes seen in patients with PT represents a traction osteophyte secondary to the high tensile loads in this area. A recent hypothesis suggests that a compressive force exists at the proximal-posterior aspect of the patellar tendon, which acts an “adaptive process” leading to the formation of an altered tissue.

It has also been proposed that the cause of PT is chronic stress overload, resulting in microscopic tears of the tendon and degeneration. Kannus speculated that tendinosis may begin with horizontal collagen tearing due to mechanical overload.

Lian et al found that volleyball players with PT performed better in a standardized series of jump and power tests than did a matched control group. Ground reaction force, knee flexion angle during landing, and external tibial torsional movement are all increased in elite volleyball players with PT. Furthermore, it is believed that eccentric force production is a primary cause of tendon microruptures. These findings suggest that the knee kinematics and forces during jumping contribute to PT. Subjects who developed PT have also been shown to be less flexible in the quadriceps and hamstring muscles. It has furthermore been shown that the incidence of PT increases as the intensity or frequency of training increases.

As the characteristic lesion in PT typically occurs in the deep posterior part of the proximal patellar tendon, it has been hypothesized that loading exposes this part of the tendon to greater strain. This hypothesis was tested in 2 recent cadaveric studies, with conflicting results. Several authors have stated that further study is necessary, specifically with regard to the differential forces applied to the proximal patellar tendon.

This study is the first to evaluate differential strains in the proximal patellar tendon in vivo. It tests the hypothesis that the posterior fibers of the proximal patellar tendon are subjected to greater tendinous forces than are the corresponding anterior fibers.

MATERIALS AND METHODS

Optic Fiber Technique

An optic fiber was used as a sensor to record the difference in forces in the proximal patellar tendon. This technique, which was first introduced by Komi et al, has previously been used in in vivo studies on the Achilles tendon and the patellar tendon. The technique entails the optic fiber being inserted through the entire cross section of the tendon and the ends being attached to a transmitter-receiver unit for light intensity monitoring. The optic fiber force sensor works on the principle of the amplitude modulation of transmitted light when the optic fiber is geometrically altered owing to the forces acting on it. Longitudinal strain in the tendon or ligament produces a negative transverse strain, thus causing a force that effectively squeezes the optic fiber.

The sensing unit is composed of a transceiver unit (2 HFBR 1414T transmitters and 2 HFBR 2416T receivers, Agilent Technologies, Santa Clara, Calif) and 2 pieces of optic fiber (300 mm in length with an outside diameter of 0.5 mm, Raytela PGR-FB 500, Toray Industries, Tokyo, Japan). The optic fibers are connected to the transceiver unit by means of ST connectors. A regulated voltage supply (of 5 V) drives a small LED, which transmits the light signal through the connected pieces of optic fiber. At the receiver end, a photodiode gives a voltage output that is proportional to the sensed light intensity. In this study, 2 optic fibers were inserted through the proximal patellar tendon, 1 anteriorly and 1 posteriorly.

Calibrating an in vivo–implanted optic fiber sensor to yield absolute forces is challenging. It was deemed unnecessary for the purposes of this study to calibrate the sensors to record forces in newtons because we were investigating only the differences in loading at 2 positions on the tendon. Standard off-the-shelf electronic components were used in building the 2 sensor channels, which caused a difference in the sensitivity of the channels of approximately 3%, as revealed by in vitro testing of the sensor in a hydraulic press. Because transducer output is also influenced by optic fiber bending, it was necessary to investigate the relative movement between skin and tendon. Finni et al measured the forces during maximum voluntary contraction on 4 volunteers, using the exact same type of fiber optic sensor. They concluded that the effect of skin movement introduced a less than 2% error on the sensor output. Erdemir et al did a cadaveric simulation of walking during which the optic fiber measurements of Achilles tendon forces were compared with known applied loads on the tendon. They found that skin movement induced high errors (24%-81% of peak forces) and that measurement errors decreased considerably after the skin was removed (10%-33% peak forces). In our study, we manually moved the skin 1 cm proximally and 1 cm distally relative to the underlying tendon with the optic fibers in situ. The manually induced errors resulted in a maximum error of 3.7% that could be found during the squat exercise, 3.4% for the step exercise, and 2% for jumping. Our results and conclusions regarding the effect of skin movement are hence in keeping with those of Finni et al. It should also be kept in mind that the effect of skin movement will be almost the same for both channels because of their close proximity, and hence the skin movement does not influence our conclusions.

Goniometer

A custom-designed goniometer was used to measure the knee flexion angles during the exercises. A variable-resistance
Both the optic fiber force sensor and the goniometer have analog outputs. The analog signals were converted into digital format for data processing with a PC. The conversion was performed with a USB-based I/O module (PMD-1608FS, Measurement Computing, Norton, Mass) with eight 16-bit single-ended analog channels, each with its own A/D converter. The anterior and posterior output channels of the sensing unit, a switch used to record the landing in the jump exercise, and the goniometer were coupled to this device through BNC cables.

Data acquisition was performed by a customized LabVIEW application (LabVIEW 7.1), which consisted of universal libraries that were supplied with the USB-based I/O module. The number of channels that needed to be scanned on the module, the number of required data points, the sampling frequency, and the voltage ranges for the sampled data were specified on the user interface. After the data collection of each trial, all sampled data were exported to Matlab (version 7.0.1.24704 [R14], MathWorks, Natick, Mass) for processing.

Data Processing

Both channels are zeroed before implantation, but after implantation there is a DC offset between the channels. This offset is attributed to 2 factors: the termination of the optic fiber ends and the pretension in the tendon (it is not possible to guarantee an absolute zero loading condition during implantation). Both factors introduced a subject-specific offset in sensor readings at zero load conditions.

Regarding the quality of the termination of the fiber optic ends, 10 fibers of the same length were cleaved and the readings taken at zero loading (ie, not implanted). The mean steady-state output for the anterior channel was 3.56 V (SD, 0.197 V; n, 10). The mean steady-state output at zero load for the posterior channel was 3.54 V (SD, 0.194 V; n, 10). This resulted in a mean offset of 2 mV between the 2 channels, which can introduce a 0.1% error in the full-scale output for all the exercises, which is negligible.22

The mean recorded steady-state DC offset between the channels after implantation was 20 mV, and we believe this is owing to the effect of a pretension in the tendon (ie, there already exists greater tension in the posterior region). However, even if this hypothesis is wrong, the reading of 20 mV can introduce a maximum error of 1% to 2% on the full-scale output for all the exercises and hence does not influence our conclusions presented in this article.

Because of these factors, we reported the sensor outputs as a deviation in the sensor readings from a reference value, and we termed this the differential output. The differential output was determined by the subtraction of the “raw” sensor signals from the reference value. The reference chosen was the smallest sensor output of the anterior channel at a physiologically minimal load condition (lower sensor outputs indicated lower forces and vice-versa). The same reference was then used on both channels, hence establishing the zero baseline according to which we reported the data. Through the comparison of the magnitudes of the differential outputs of the posteriorly and anteriorly placed optic fibers, it was possible to state whether the forces were larger in the one compared with the other despite the inability to quantify the results in absolute force values.

A last processing step was to calculate a 10-point running average of the data to filter out sampling noise.

In Vivo Study

Participants. Seven healthy males with no previous history of PT, knee injury, or knee pain requiring consultation with a doctor volunteered for this study (Table 1). They were informed of all the risks of the study, they gave their written consent for participation, and they were free to stop the experiment at will. The study was approved by the ethics committee of the authors’ university.
Experiment protocol. An ultrasound examination of the patellar tendon was performed before the insertion of the optic fibers. The transverse width of the proximal patellar tendon, the anteroposterior diameter of the proximal patellar tendon, the length of the patellar tendon, and the presence or absence of a hypoechoic lesion in the proximal patellar tendon were recorded.

With the patient supine and the knee flexed to 90°, 2 sterile 20-gauge spinal needles were inserted into the proximal patellar tendon under ultrasound guidance with the use of an aseptic technique and after the infiltration of local anesthetic. The first 20-gauge spinal needle was passed through the tendon from lateral to medial, 1 to 2 mm anterior to the posterior border of the tendon. The second needle was placed 1 to 2 mm posterior to the anterior border of the tendon and parallel to the first needle. The obturator of each spinal needle was removed, and a 0.5-mm optic fiber was fed through each needle. The needles were removed, leaving the optic fibers in the tendon (Figure 2). Transmitter-receiver units were attached to the free ends of both optic fibers.

The positions of the needles were verified with ultrasound (Figure 3) to be within 5 to 10 mm of the apex of the patella within the anterior half of the patellar tendon (anterior fiber) and within the posterior half of the patellar tendon (posterior fiber).

The hinged knee brace fitted with the goniometer was fitted to the leg. The transmitter and receiver units of the 2 optic fibers were attached to the light source and the receiver mounted on the brace.

Measurements were recorded during the following activities:

1. Closed kinetic chain eccentric and concentric quadriceps contraction during a 1-leg squat:
   - Concentric quadriceps contraction from 110° of knee flexion to full extension.
   - Eccentric quadriceps contraction from full extension to 110° of knee flexion.
2. Open kinetic chain concentric quadriceps contraction with a 10-kg weight attached to the foot:
   - Concentric: active knee extension from 90° of flexion to full extension.
   - Eccentric: controlled knee flexion from full extension to 90° of knee flexion.
3. Step up and step down:
   - With the right leg as the leading leg.
4. Jump from a height of 30 cm:
   - Landing on the right leg with hip and knee flexed to the participant's discretion.

On completion of the experiment, the optic fibers were removed, and an adhesive dressing was applied.

<table>
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<tr>
<th>Participant</th>
<th>Age, y</th>
<th>Sex</th>
<th>Height, cm</th>
<th>Weight, kg</th>
<th>Body Mass Index, kg/m²</th>
<th>Q Angle, deg</th>
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<td>Male</td>
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<td>78</td>
<td>24.1</td>
<td>14</td>
</tr>
<tr>
<td>Mean ± SD</td>
<td>26.4 ± 3.9</td>
<td>180.3 ± 8</td>
<td>80.7 ± 8.1</td>
<td>24.8 ± 1.5</td>
<td>12.4 ± 1.1</td>
<td></td>
</tr>
</tbody>
</table>

TABLE 1
Anthropometric Data of the Study Participants

Figure 2. Position of the optic fibers in the patellar tendon.
Statistical Methods
The means of the anterior and posterior peak differential signal deflections were compared using repeated-measures analysis of variance. Normal probability plots were inspected to check for deviations from normality and possible outliers, and none were found that could have significantly influenced the results. Means and SDs were calculated for descriptive purposes. A minimum significance level of $P \leq .05$ was set for all statistical tests.

RESULTS
The sonographic characteristics of the proximal patellar tendon are represented in Table 2.

The positions of the 2 fibers were well within the anterior and posterior halves of the proximal patellar tendon as confirmed by sonographic measurement (Table 3).

A hypoechoic lesion in the posterior aspect of the proximal patellar tendon was noted in 1 of the 7 participants (participant 5). We did not notice any obvious difference between this person’s results and those of the other 6. In addition, normal probability plots were inspected for possible outliers, and none were found. The results from each exercise are described below.

**Closed Kinetic Chain Eccentric and Concentric Quadriceps Contraction During a 1-Leg Squat**

The peak differential outputs were greater in the posterior fiber than in the anterior fiber in all 7 participants (Table 4). This finding was statistically significant ($P = .0097$ for the concentric contraction and $P = .0087$ for the eccentric contraction). The peak differential output during the concentric contraction occurred at a mean of $102.4^\circ \pm 8.8^\circ$ of knee flexion in the anterior fibers and at $94.8^\circ \pm 18.9^\circ$ of knee flexion in the posterior fibers (Figure 4). During the eccentric phase of the exercise, this occurred at $97.9^\circ \pm 14.2^\circ$ of knee flexion in the anterior fibers and at $94.9^\circ \pm 16^\circ$ of knee flexion in the posterior fibers.

**Open Kinetic Chain Concentric Quadriceps Contraction**

The posterior fibers had a greater peak differential output than did the anterior fiber in all 7 participants (Table 5). This trend was shown to be statistically significant ($P = .0078$ for the concentric contraction and $P = .0075$ for the eccentric contraction). The peak differential output during the concentric contraction occurred at a mean of $3.4^\circ \pm 4.8^\circ$ of knee flexion in the anterior fibers and at $4.8^\circ \pm 9.5^\circ$ of knee flexion in the posterior fibers.
flexion in the posterior fibers. During the eccentric phase of the exercise, this occurred at 10.1° ± 12.4° of knee flexion in the anterior fibers and at 10.3° ± 15.7° of knee flexion in the posterior fibers.

### Step Exercise

Once again, the posterior fiber showed a larger peak differential output than did the anterior fiber in all 7 participants (Tables 6 and 7). This trend was once again statistically significant ($P = .0020$ for the step-up and $P = .0023$ for the step-down). There was a greater peak differential output on the step-down than on step-up in both the anterior ($P = .0250$) and the posterior ($P = .0280$) fibers.

### Jump From a Height of 30 cm

The results of this exercise were the most striking (Figure 5). All 7 participants had a greater differential signal output in the posterior optic fiber than in the anterior optic fiber (Table 8). This finding was statistically significant ($P = .0019$). The knee flexion angles at peak differential output ranged from 32.2° to 96.7° (mean, 54.5°) for the anterior fibers and from 32.2° to 57.8° (mean, 45°) for the posterior fibers.

**Figure 4.** Example of a squat exercise (participant 5).

**TABLE 4**

<table>
<thead>
<tr>
<th>Participant</th>
<th>Concentric Contraction</th>
<th>Eccentric Contraction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Anterior, V</td>
<td>Posterior, V</td>
</tr>
<tr>
<td>1</td>
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<td>0.86</td>
</tr>
<tr>
<td>2</td>
<td>0.19</td>
<td>0.56</td>
</tr>
<tr>
<td>3</td>
<td>0.40</td>
<td>1.72</td>
</tr>
<tr>
<td>4</td>
<td>0.47</td>
<td>1.68</td>
</tr>
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<td>5</td>
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</tr>
<tr>
<td>6</td>
<td>0.25</td>
<td>0.73</td>
</tr>
<tr>
<td>7</td>
<td>0.23</td>
<td>0.37</td>
</tr>
<tr>
<td>Mean ± SD</td>
<td>0.41 ± 0.27</td>
<td>1.0 ± 0.55</td>
</tr>
</tbody>
</table>

*Concentric contraction, the posterior maximum forces are larger than the anterior maximum forces ($P < .05$). Eccentric contraction, the posterior maximum forces are larger than the anterior maximum forces ($P < .05$).
DISCUSSION

The transverse width of the proximal patellar tendon in our study of 27.3 ± 3.5 mm correlated well with the findings of an MRI study by El-Khourny et al\textsuperscript{8} (31.3 ± 9.3 mm). The AP diameter of 4.6 ± 0.6 mm in our study was midway between the 3.7 ± 1.2 mm of El-Khourny et al\textsuperscript{15} and the 5.5-mm AP diameter of an earlier MRI study by Johnson et al.\textsuperscript{15}

The 1 participant with a hypoechoic lesion in the proximal posterior aspect of the patellar tendon was involved in recreational sports activity only. This finding of an asymptomatic hypoechoic lesion has been shown before in previous

\begin{table}
\centering
\caption{Peak Differential Output With an Open Kinetic Chain Concentric Quadriceps Contraction\textsuperscript{a}}
\begin{tabular}{lccc}
\hline
Participant & Anterior, V & Posterior, V & Ratio = Posterior/Anterior \\
\hline
1 & 0.22 & 0.58 & 2.6 \\
2 & 0.13 & 0.51 & 3.8 \\
3 & 0.23 & 1.7 & 7.3 \\
4 & 0.18 & 1.0 & 5.6 \\
5 & 0.30 & 1.2 & 3.8 \\
6 & 0.17 & 0.70 & 4.1 \\
7 & 0.21 & 0.35 & 1.9 \\
\hline
Mean ± SD & 0.21 ± 0.054 & 0.86 ± 0.47 & 4.2 ± 1.8 \\
\end{tabular}
\begin{tabular}{lccc}
\hline
Participant & Anterior, V & Posterior, V & Ratio = Posterior/Anterior \\
\hline
1 & 0.20 & 0.58 & 2.8 \\
2 & 0.13 & 0.51 & 3.9 \\
3 & 0.23 & 1.7 & 7.2 \\
4 & 0.21 & 1.1 & 5.1 \\
5 & 0.30 & 1.2 & 3.9 \\
6 & 0.19 & 0.71 & 3.8 \\
7 & 0.22 & 0.36 & 1.8 \\
\hline
Mean ± SD & 0.21 ± 0.051 & 0.88 ± 0.47 & 4.1 ± 1.7 \\
\end{tabular}
\textsuperscript{a}Concentric contraction, the posterior maximum forces larger than the anterior maximum forces (\(P < .05\)). Eccentric contraction, the posterior maximum forces are larger than the anterior maximum forces (\(P < .05\)).
\end{table}

\begin{table}
\centering
\caption{Peak Differential Output With a Step-up Exercise\textsuperscript{a}}
\begin{tabular}{lccc}
\hline
Participant & Anterior, V & Posterior, V & Ratio = Posterior/Anterior \\
\hline
1 & 0.090 & 0.59 & 6.2 \\
2 & 0.11 & 0.45 & 3.9 \\
3 & 0.48 & 1.53 & 3.2 \\
4 & 0.14 & 0.75 & 5.5 \\
5 & 0.27 & 0.93 & 3.5 \\
6 & 0.18 & 0.72 & 4.1 \\
7 & 0.25 & 0.41 & 2.4 \\
\hline
Mean ± SD & 0.22 ± 0.13 & 0.77 ± 0.38 & 4.1 ± 1.3 \\
\end{tabular}
\begin{tabular}{lccc}
\hline
Participant & Anterior, V & Posterior, V & Ratio = Posterior/Anterior \\
\hline
1 & 0.14 & 0.61 & 4.42 \\
2 & 0.14 & 0.49 & 3.6 \\
3 & 0.46 & 1.59 & 3.43 \\
4 & 0.18 & 0.75 & 4.05 \\
5 & 0.32 & 1.09 & 3.42 \\
6 & 0.2 & 0.76 & 3.82 \\
7 & 0.25 & 0.44 & 2.55 \\
\hline
Mean ± SD & 0.24 ± 0.12 & 0.82 ± 0.40 & 3.6 ± 0.59 \\
\end{tabular}
\textsuperscript{a}The posterior maximum forces are larger than are the anterior maximum forces (\(P < .05\)).
\end{table}

\begin{table}
\centering
\caption{Peak Differential Output With a Step-down Exercise\textsuperscript{a}}
\begin{tabular}{lccc}
\hline
Participant & Anterior, V & Posterior, V & Ratio = Posterior/Anterior \\
\hline
1 & 0.19 & 0.78 & 3.99 \\
2 & 0.17 & 0.57 & 3.41 \\
3 & 0.53 & 1.79 & 3.41 \\
4 & 0.19 & 0.83 & 4.45 \\
5 & 0.57 & 1.27 & 2.21 \\
6 & 0.4 & 0.82 & 2.12 \\
7 & 0.53 & 0.86 & 1.63 \\
\hline
Mean ± SD & 0.37 ± 0.18 & 0.99 ± 0.41 & 3.0 ± 1.1 \\
\end{tabular}
\begin{tabular}{lccc}
\hline
Participant & Anterior, V & Posterior, V & Ratio = Posterior/Anterior \\
\hline
1 & 0.19 & 0.78 & 3.99 \\
2 & 0.17 & 0.57 & 3.41 \\
3 & 0.53 & 1.79 & 3.41 \\
4 & 0.19 & 0.83 & 4.45 \\
5 & 0.57 & 1.27 & 2.21 \\
6 & 0.4 & 0.82 & 2.12 \\
7 & 0.53 & 0.86 & 1.63 \\
\hline
Mean ± SD & 0.37 ± 0.18 & 0.99 ± 0.41 & 3.0 ± 1.1 \\
\end{tabular}
\textsuperscript{a}The posterior maximum forces are larger than are the anterior maximum forces (\(P < .05\)).
\end{table}

\begin{table}
\centering
\caption{Peak Differential Signal Output With a Jump Exercise\textsuperscript{a}}
\begin{tabular}{lccc}
\hline
Participant & Anterior, V & Posterior, V & Ratio = Posterior/Anterior \\
\hline
1 & 0.19 & 0.78 & 3.99 \\
2 & 0.17 & 0.57 & 3.41 \\
3 & 0.53 & 1.79 & 3.41 \\
4 & 0.19 & 0.83 & 4.45 \\
5 & 0.57 & 1.27 & 2.21 \\
6 & 0.4 & 0.82 & 2.12 \\
7 & 0.53 & 0.86 & 1.63 \\
\hline
Mean ± SD & 0.37 ± 0.18 & 0.99 ± 0.41 & 3.0 ± 1.1 \\
\end{tabular}
\begin{tabular}{lccc}
\hline
Participant & Anterior, V & Posterior, V & Ratio = Posterior/Anterior \\
\hline
1 & 0.19 & 0.78 & 3.99 \\
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3 & 0.53 & 1.79 & 3.41 \\
4 & 0.19 & 0.83 & 4.45 \\
5 & 0.57 & 1.27 & 2.21 \\
6 & 0.4 & 0.82 & 2.12 \\
7 & 0.53 & 0.86 & 1.63 \\
\hline
Mean ± SD & 0.37 ± 0.18 & 0.99 ± 0.41 & 3.0 ± 1.1 \\
\end{tabular}
\textsuperscript{a}The posterior maximum forces are larger than are the anterior maximum forces (\(P < .05\)).
\end{table}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure5.png}
\caption{Differential output during a jump exercise (participant 3).}
\end{figure}
studies and provides further evidence that ultrasonographic appearance and clinical symptoms do not correlate precisely. It has, however, previously been shown that in elite junior basketball players, the presence of an asymptomatic ultrasonographic hypoechoic area was associated with a 4 times greater risk of developing PT.

The 2 previous in vivo studies using this technique in the Achilles tendon and the patellar tendon noted that the insertion of a needle through the tendon was virtually pain free. The experience of our first 2 participants did not, however, bear this out, hence our attempt to achieve better analgesia. The resultant excellent anesthetic effect of the infiltration of local anesthetic adjacent to the deep margin of the proximal tendon was of particular interest, and it can be postulated that this region of the tendon receives rich innervation from the underlying fat pad.

This was the first study to evaluate the differential tendinous forces in the proximal patellar tendon in vivo. Our results indicated that an optic fiber located in the posterior region of the patellar tendon was subjected to greater tensile forces than was an optic fiber located in the corresponding anterior region. This finding was statistically significant for all the exercises performed in this study, which included an open and closed kinetic chain exercise, a step exercise, and a jump exercise. The greatest signal deflections were reported for the jump exercise.

Two previous cadaveric studies assessing differential tensile strain in the proximal patellar tendon showed conflicting results. This could be attributed to methodological differences.

Almekinders et al measured strain patterns in 8 patellar tendons with the use of a buckle sensor. When a 45-N load was applied to the quadriceps muscle with the knee in full extension, a strain increase in the central proximal posterior region of the tendon was observed. However, strain decreased in the anterior region of the tendon. Relatively low loads and velocities were used, and the authors mentioned that higher loads and velocities could transfer more tensile load to the posterior tendon surface.

Basso et al measured tensile strain in the anterior and posterior fibers of 10 cadaveric knees with a technique of documenting changes in suture length. Quadriceps loading in this study caused significantly greater strains in the posterior fascicles between 60° and 90° of knee flexion. A significantly higher load of 1 kN was used in this study compared to the 45-N load in the previously mentioned study.

Both these cadaveric studies were performed on a much older study population, although PT occurs in a young, athletically active population. The techniques of strain measurement used required significant soft tissue dissection and the removal of retinacular structures. Our findings, however, are in agreement with the second study, which found that quadriceps loading in knee flexion caused significantly greater strains in the posterior fascicles.

The peak signal outputs toward the end of extension during the open kinetic chain quadriceps contraction suggest that the last ±10° of knee extension should be avoided during a rehabilitation program when resisted knee extension exercises are performed. When squat exercises are performed, deep knee flexion should also be avoided, as peak deflections during these exercises occurred from 94°. A safe recommendation would be to avoid squat exercises of greater than 80° of knee flexion.

This study had some limitations. One of these was that the optic fiber sensors were not calibrated, and we were therefore not able to quantify the forces encountered. We accept this as a limitation but would argue that the aim of the study was to assess the differential forces in the 2 locations, and we are satisfied that our methods met this aim. Another limitation was that the small numbers precluded meaningful deductions regarding the differences between eccentric and concentric exercises and knee flexion angles at peak differential output during some of the exercises. There was, however, a trend toward greater differential signal output during eccentric exercises than during concentric exercises, although this was not statistically significant in any of the relevant exercises. This was in keeping with previous findings regarding the link between eccentric force production and the overload theory.

This was the first in vivo study to evaluate differential forces between the anterior and the posterior fibers of the proximal patellar tendon. The results clearly showed higher forces in the posterior fibers than in the anterior fibers. This supports the repeated tensile-overload theory of PT. It also showed that deep-squat exercises and jumping result in very high tensile forces in the patellar tendon.

ACKNOWLEDGMENT

This research was partly funded by research grants from Stellenbosch University and the South African Orthopaedic Association.

REFERENCES