INTRODUCTION
The moment arm (ma) of a tendon is a crucial quantity for understanding musculoskeletal dynamics as it defines how the linear force within a muscle is transformed into a torque. For most tendons this is a fairly well established parameter as it can be defined from the kinematics of the tendons’ origins, insertions, and/or wrapping points. Yet, for the quadriceps this relationship is complicated by the fact that the patella serves as an intermediary (a dynamic fulcrum) between the quadriceps and tibia. Thus, the transfer of the quadriceps force into a torque on the tibia cannot be directly calculated. Therefore, the term effective quadriceps moment arm (EQma) was coined to define the ability of the quadriceps to generate a torque on the tibia [1]. To date, no study has quantified this parameter during dynamic in vivo movement. Furthermore, the critical question of how patellofemoral (PF) kinematics remains unresolved. Specifically, patella alta has been widely implicated as the source of a reduced EQma in patients with cerebral palsy, contributing to an already weakened extensor mechanism [2,3]. In contrast, a recent study demonstrated that individuals with patella alta had a significantly larger EQma [4]. Therefore the purpose of this study was to determine, using in vivo dynamic MRI, the EQma during a knee extension exercise in a large group of asymptomatic controls. A secondary goal of the study was to determine if the EQma was correlated with PF or patellar tendon moment arm (PTma), relative to the IHA, through integration of the velocity data. This enabled quantification of the 3D PF kinematics and TF Instantaneous Helical Axis (IHA), as well as the patellar tendon moment arm (PTma), relative to the IHA, throughout the motion cycle [6]. Since the force of the patellar tendon acts directly on the tibia, the PTma can be directly calculated from the PF and TF kinematics (Figure 1). In contrast, the quadriceps tendon acts through the patella to create a moment on the tibia. Thus, its effective ma, EQma, is quantified based on the ratio of the patellar tendon to the quadriceps force (Fp/Fq), calculated using the moment balance equation for the patella relative to the PF point of contact (PC) (assumed to be the center of PF line of contact in the mid-patellar image):

\[ \sum M_{PC} = F_p \times ma_p - F_Q \times ma_Q = 0 \]  \hspace{1cm} (1)

\[ F_p = F_Q \times ma_q/ma_p \]  \hspace{1cm} (2)

ma_p: ma of the patellar tendon, relative to PC
ma_q: ma of the quadriceps tendon, relative to PC

Given that the moment on the tibia (relative to the IHA) created by the patellar tendon (MTib,PT) is:

\[ M_{Tib,PT} = PTma \times F_p \]  \hspace{1cm} (3)

The moment on the tibia from the quadriceps (MTib,Q) can be calculated by substituting the definition of Fp from equation 2 into equation 3 and then rearranging equation 3:

\[ M_{Tib,Q} = PTma \times (ma_q/ma_p) \times F_Q \]  \hspace{1cm} (4)

\[ M_{Tib,Q} = EQma \times F_Q \]  \hspace{1cm} (5)

Therefore:

\[ EQma = PTma \times (ma_q/ma_p) \]  \hspace{1cm} (6)
Since the CPC data were acquired temporally, all kinematic data were interpolated to single knee angle increments. The EQma required a lengthy visual image analysis, thus the analysis was performed at three distinct knee angles (10°, 20°, and 30°). The relationship between knee angle and image number was derived through the CPC kinematic data. If a specific knee angle fell between two images, both images were analyzed and the EQma was calculated for the specific knee angle using interpolation. Due to variations in subjects’ ranges of motion within the MR, not all subjects were represented at the extremes of the motion cycle. Average PTma values that did not include at least 11 subjects were eliminated. Pearson’s correlations were calculated between the ma variables and both the PF and the TF kinematics (p < 0.05 was considered significant).

RESULTS AND DISCUSSION

Both the PTma and EQma consistently trended up as the knee angle decreased (Figure 2). The PTma matched previous findings [6]. The ratio (maQ/maP) agreed well in terms of shape and value with the results of Yamaguchi et al [1]. In both studies, the ratio increased as the knee angle decreased and crossed above 1.0 at a knee angle just greater than 20° (Figure 3). Thus, at knee angles less than 20°, the patella improves the mechanical efficiency of the quadriceps, while at higher knee angles it detracts from this efficiency. Since Yamaguchi et al [1] used the TF point of contact as the reference for the PTma, the EQma cannot be compared directly to this work. In contrast, the EQma, ratio, and PTma were all different in both shape and value in comparison to the work of Ward et al [4]. One of the largest sources for these differences can be attributed to the TF IHA, which, in the current study was directly calculated from the TF kinematics, whereas in the previous study it was estimated using the crossing points of the anterior and posterior cruciate ligaments. Another potential source of error was the consistency at which knee angles could be measured. In the current study, the knee angle was directly calculated from bone geometry and tracked using the CPC data, whereas in the previous study the knee angle was measured externally and the subjects were asked to maintain this angle throughout the scan.

In regards to the second aim, the PF inferior-superior location was weakly, but significantly correlated with EQma at 10 and 20 degrees but not at 30 degrees (Table 1). At 10° and 30° knee angles, the PF inferior-superior location was moderately and weakly correlated, respectively, with the ratio. While the inferior-superior position of the patella appears to play a role in the EQma at smaller knee angles, its weak correlation indicates that there are other factors involved.

There are two primary limitations to this study. The first is that in order to identify the contact point between the cartilage of the patella and the femur, subjective visual analysis of the MRIs was required. The excellent inter- and intra-rater reliability for the EQma, as evidenced by the intraclass correlation coefficients (0.93-0.94), indicate that this did not likely add imprecision to the data. Second, in order to find a unique relationship between the Fp and Fq, the analysis was forced to remain two-dimensional. Although the 3D quadriceps moment arms have been calculated relative to the patellar center [7], future work will be needed to relate the quadriceps force to the tibial torque in three-dimensions.

CONCLUSIONS

As this is the first study to characterize the EQma in vivo during dynamic volitional activity in a large group of asymptomatic controls, it will serve as a foundation upon which to explore how pathological conditions such as patellofemoral pain and cerebral palsy affect the EQma as compared to asymptomatic controls. In addition it provides fundamental data for future modeling studies.

REFERENCES


Table 1: Correlations between the inferior-superior location of patella and the ratio, PTma, and EQma at 10°, 20° & 30°. * indicates significance at a p-level of 0.05

<table>
<thead>
<tr>
<th>Knee angle (°)</th>
<th>SI:Ratio</th>
<th>SI:PTma</th>
<th>SI:EQma</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.56*</td>
<td>0.08</td>
<td>0.41*</td>
</tr>
<tr>
<td>20</td>
<td>0.27</td>
<td>0.14</td>
<td>0.32*</td>
</tr>
<tr>
<td>30</td>
<td>0.43*</td>
<td>0.13</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Figure 2: PTma and EQma vs. Knee angle with 1 SD bars

Figure 3: Ratio (maQ/maP) vs. Knee angle with 1 SD bars