THE INFLUENCE OF PATELLOFEMORAL KINEMATICS ON THE EFFECTIVE QUADRICEPS MOMENT ARM: A DYNAMIC IN VIVO STUDY

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INTRODUCTION
The moment arm (ma) of a tendon is a crucial quantity for musculoskeletal dynamics as it defines how the linear force within a muscle is transformed into a torque. 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 term effective quadriceps moment arm (EQma) was coined to define the quadriceps indirect ability to generate a torque on the tibia [1]. To date, no study has quantified the EQma during dynamic in vivo movement. Furthermore, the critical question of how patella-femoral (PF) kinematics may influence the EQma 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]. Yet, a recent study demonstrated that individuals with patella alta had a significantly larger EQma [3]. Therefore the purpose of this study was to determine the EQma during a knee extension exercise in a large group of asymptomatic controls, using in vivo dynamic MRI. A secondary goal of the study was to determine if the EQma was correlated with PF or tibiofemoral (TF) kinematics.

METHODS
Forty-one knees (19M/22F, age = 26.2 ±7.9 years, height = 170.9 ± 10.8cm, mass = 69 ±13.4kg) were included within this IRB approved study. All participants were placed supine in an MR imager (1.5T, GE Medical Systems, Milwaukee, WI) and were asked to cyclically flex and extend their knee while a dynamic cine-phase contrast (CPC) MR image set (x,y,z velocity and anatomic image frames) was acquired [4]. Dynamic cine images (anatomic image frames only) were also acquired in three axial planes to establish anatomical coordinate systems. The kinematics of each bone were derived through integration of the velocity data. This enabled the 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 [5]. The EQma was quantified based on the ratio of the patellar tendon to quadriceps force (Fp/Fq, Fig 1), 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):

$$EQma = PTma*(Fp/Fq) = PTma*(maQ/ maP)$$

maP: ma of the patellar tendon, relative to PC
maQ: ma of the quadriceps tendon, relative to PC

Since the CPC data were acquired temporally, all kinematic data were interpolated to single knee angle (KA) increments. The EQma required a lengthy visual image analysis, thus the analysis was performed at three distinct KAs (10°, 20°, and 30°). If a specific KA fell between two images, both images were analyzed and the EQma was calculated using the moment balance equation.
calculated using interpolation. Correlations were calculated between the ma variables (the EQma, maQ/maP ratio, and PTma) both the PF and the TF kinematics (significance: p<0.05).

RESULTS AND DISCUSSION

Both the PTma and EQma consistently trended up as the KA decreased (Fig 2). The ratio of 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 KA decreased and crossed above 1.0 at a KA just greater than 20°. Thus, at KAs less than 20°, the patella improves the mechanical efficiency of the quadriceps, while at higher KAs 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, maQ/maP ratio, and PTma were all different in both shape and value in comparison to the work of Ward et al [3]. 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 variance was the consistency at which KAs could be measured. In the current study, the KA was directly calculated from bone geometry and tracked using the CPC data, whereas in the previous study the KA was measured externally and the subjects were asked to maintain this static angle throughout the scan.

There were two primary limitations to this study. The first is that in order to identify the PF point of contact point, 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), indicated 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 ma has been calculated relative to the patellar center [6], future work will be needed to relate the 3D quadriceps force to the tibial torque.

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
