TECHNICAL NOTE

Changes of the Patellar Tendon Moment Arm Length in Different Knee Angles: A Biomechanical in Vivo Study

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Abstract

Patellar tendon moment arm length (PTma) changes at different knee flexion angles have not been determined in in vivo studies. We aimed to determine PTma in four different knee angles using Magnetic Resonance Imaging (MRI) to predict in vivo changes in the moment arm length from different knee angles during running.
PTma was measured as the perpendicular distance from muscle–tendon line of action to the knee joint axis of rotation at 0° (full extension), 20°, 40°, and 60° flexion of knee by using MRI method. Repeated measure ANOVA method was applied to compare the moment arm length among four degrees of knee flexion ($P<0.05$). A regression analysis was used to predict the PTma during different knee joint angles.
The PTma in the four angles at 0°, 20°, 40°, and 60° of knee flexion were 42.55±4.20, 39.91±2.98, 37.73±2.87, and 36.18±2.90 mm, respectively ($P<0.05$). The regression analysis provided an equation to predict the PTma from different knee joint angles during running.
PTma values decreased from knee extension to flexion in a linear manner. These findings have important implications for estimating PTma using a regression equation model from different knee joint angles.

Level of evidence: V

Keywords: Knee, MRI, Patellar tendon moment arm length, PTma

Introduction

Muscle force estimation is essential in biomechanical study, training, and assistance device fields that are measured from moment of joints (1). Estimation of muscle forces requires knowledge of the muscle and tendon moment arm length. Moment arm length has been defined as the perpendicular distance from the axis of joint rotation to the muscle action line. Knowledge of any changes in moment arm with respect to joint angle allows estimating the muscle force accurately throughout the range of motion and has importance in muscle modeling (2). The main moment arm affecting the knee joint is the patellar tendon moment arm as the leverage of the effective force that is transmitted to the tibia due to quadriceps muscle contraction during the knee joint extension (3).

Direct measurement of muscle forces is highly invasive. In previous studies, most of the data on patellar tendon moment arm length (PTma) have been obtained from measurements on cadavers or in vivo measurements at resting position with unloaded knee joints (4, 7-8). In recent in vivo studies, moment arm lengths have been determined by X-ray and ultrasound methods (7, 9). However, these methods have generally utilized the tendon excursion and tracked only the musculotendon junction during passive joint

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rotation. Furthermore, these methods lack the ability to evaluate the tendon expansion due to the active muscle contractions (7, 9, 10).

In recent years, several non-invasive methods have become common to estimate muscle or tendon moment arm length. MRI (Magnetic resonance imaging) has the ability to assess the moment arms for the muscle groups crossing various joints, such as knee, in in vivo studies. Apart from its nonionizing radiation, MR imaging technique is superior to X-ray by allowing a precise delineation of the patellar tendon tracking due to a clear tissue intensity contrast (11). MRI studies are able to determine muscle-tendon moment arm lengths directly by measuring the distance between a joint axis of the rotation and a line of action (10). On the other hand, data on moment arm lengths have recently been obtained at a singular joint angular situation and with subjects at resting position (3).

It is hypothesized that any changes in knee joint angle in in vivo studies affects the tendon direction, the status of bones, and the ligaments relative to each other that may affect the moment arm length directly (12). However, no studies has measured in vivo patellar tendon moment arm lengths at several knee flexion angles from three-dimensional (3-D) MRI images.

The aim of the present study was to investigate patellar tendon moment arm length (PTma) changes in four knee angles by using MRI technique to establish an equation to estimate the PTma in different knee angles.

Technical Note

Participants

Twenty five healthy volunteers with mean age of 30.1±5.9 years, weight of 70.7±11.5 kg, and height of 172.4±10.8 cm were randomly enrolled in this study. None of the subjects had history of previous knee symptoms. The participants were excluded from the study if they had any knee pathology, prior surgery of the knee, or any contraindications to MR imaging (13). Each subject filled out a written informed consent. The methods were approved by the Ethics Committee of Babol University of Medical Sciences (#: MUBABOL.HRI. REC.1395.110).

Knee joint angle measurement

Knee flexion and extension were investigated in a standardized assessment. A goniometer was used to measure the range of motion while the participant actively extended or flexed their knees. The goniometer axis was located at the intersection of the thigh and leg on the lateral femoral condoyle as the knee center of rotation. The stationary arm was placed along the line from the knee joint to the greater trochanter of the hip at the lateral side of the thigh. The moving arm was placed along the lateral side of the fibula (from the center of knee rotation to the ankle lateral malleolus) (14).

MRI protocol

Participants laid supine position with extended hip and flexed knee to allow maximum range of knee motion inside a magnetic resonance imaging unit (1.5 T, GE model, USA). A body array coil with scout reception was utilized in the anatomical planes and T1-weighted 3D fast low-angle shot (F.L.A.S.H.) sequence in lateral plane. The lower extremity was scanned from popliteal fossa to two-thirds of the thigh from distal (about 18 cm above the proximal patellar pole). The MRI functional reception items were repetition time (TR) 700 ms, echo time (ET) 10 ms, flip angle (FA) 358, 200 £ 256 pixel matrix, a 220-mm field of view, 5mm thickness, and 1mm interslice gap. The whole scanning time was 6 minutes. The 3D Doctor software (version 4.0; Able Software, Lexington, MA, USA) was used for 3D reconstruction of 2D MRI slices.

The PTma was measured as the perpendicular distance from the tendon action line to the knee joint center of rotation at four angles (in degree) of 0° (full extension), 20°, 40°, and 60°. The lateral and medial condyles were shaped with circles while the centers of the circles were derived as representatives of the posterior aspect of the condyles to measure the center of knee rotation (12). The joint axis of rotation was achieved by the axis passing through the two centers. The midpoint between the center of the lateral and medial condyles was defined as the center of rotation in 2D analysis when superimposed onto each other [Figure 1] (12).

Statistical analysis

PTmas were averaged at each angle and reported over the angle ranges attained by all participants. The Shapiro–Wilk test confirmed the normal distribution of the data. Regression analysis was used to provide an equation for the graph so that we can make predictions about the moment arms lengths changes in different angles of knee angle. Furthermore, a repeated measure was used to evaluate any significant differences in moment arm values among the four angles of knee flexion that was considered significant at $P<0.05$.

Results

MRI images analyses showed that the PTma in 0°, 20°, 40°, and 60° of knee flexion was 42.55±4.2, 39.9±3, 37.7±2.9, and 36.2±2.9 mm, respectively. As shown in Figure 2, the moment-arm length decreased from extension to flexion in a linear slope. Regression analysis provided an equation to predict the PTma in different knee joint angles (Equation 1):

$$y=-0.1065x+42.286 \quad (1)$$

Where y represents the moment arm length and x is the knee flexion angle.

Findings showed significant differences among knee moment arm length for all selected knee angles ($P<0.001$). The moment arm lengths were significantly decreased about 6.2% from full extension (0°) to 20° of knee flexion; 5.46% from 20° of knee flexion to 40°, and 4.11% from 40° of knee flexion to 60°.

Figure 1. Measuring of patellar tendon (PT) moment-arm. Medial and lateral condyles were fitted with circles and the axis passing over the centers of the condyles was considered as the center of joint rotation in two and three dimensions. (a) Posterior view and (b) sagittal view (12).

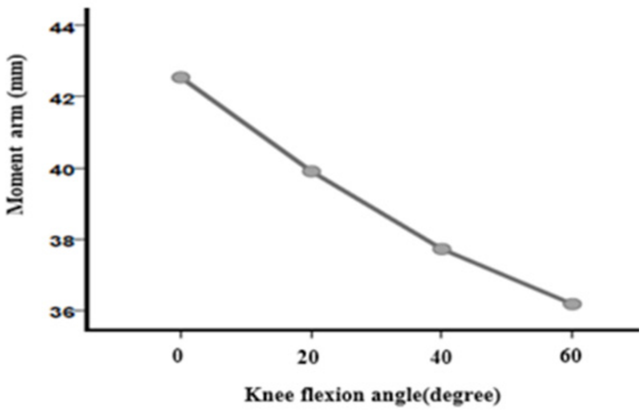

Figure 2. The moment arm values of patellar tendon in several angles of knee flexion.

Discussion

Our first specific aim was to determine the PTma which effectively alters the quadriceps muscle force to tibial rotation (15). Our results showed a similarity to those of Sheehan's (2007) in which the PTma reduced from full extension to flexion (13). Furthermore, Buford et al. (1997) used tendon excursion method in cadaver specimens and resulted in maximum and minimum values of 51 mm and 27 mm, respectively, during knee flexion (16). Tsaopoulos et al. (2007) measured the PTma by MRI regarding to the tibiofemoral contact point (PTCP) only at the rest position which indicated that the obtained values ranged from 33 to 42 mm (15). In accordance with this study, our findings showed that the PTma ranged from 36 to 42 mm at full knee extension.

The values of moment arm attained in this study is noticeably different from the previously reported values. Gill and O'Connor (1996) showed no differences in extension and flexion moment-arm lengths by using biarticulating two-dimensional modelling. Any changes in muscle–tendon volume can change the muscle line of action and as a result, its moment-arm. Obviously, neglecting the effects of muscular contraction will lead to fundamental errors in calculation of musculoskeletal forces (17). In this regard, Kellis and et al. (2015) measured the PTma in 30° knee flexion by MRI and reported its value as 51.7±5.3 mm (12). Tsaopoulos and et al. investigated the effect of knee joint flexion angle on PTma. They reported that the PTma knee joint angle of relation has an inverted U shape. Also the PTma showed to increase at midrange knee flexion angles and was lesser near full knee extension. This trend displays the mechanical advantage at midrange of flexion and disadvantage of the extensor muscles at the end of knee extension and flexion. The largest enhancements of the PTma from resting position to maximal muscle contraction were detected at 15° and 20° of knee flexion for the isokinetic and isometric extension, respectively. These findings may be described by the fact that the peak of muscle contraction between 15° and 30° of knee flexion resulted in anterior displacement of the tibia and then this force can be reduced by increasing the knee flexion (3). Their finding is in disagreement with our study that showed the larger PTma which was 42.55 mm in 0° of knee flexion (full extension) and 36.18 mm in 60° of knee flexion. Differences in the measured PTma at several joint angles may be related to following reasons (a) anthropometric variations in the subjects or in the cadaveric species in various studies,

(b) differences in the condition of the tissue (in vitro vs. in vivo), and (c) differences in the direction and value of the external resistive forces and the internal forces of muscles, ligaments, and other joint reaction forces (9).

Some studies have suggested equations based on cadaveric measurements that explain alterations of the moment arm values as a function of limb length in several knee musculotendon units (but not PT specifically) (18). However, in our study, linear PTma-angle relationship was observed at given knee flexion angles. Since the knee flexion angle and as a result the knee instant center of rotation changes during the dynamics activities, the PTma changes as well. The predicted moment arm lengths are needed for estimation of knee contact forces during in vivo activities through inverse dynamics in the field of biomechanics. The estimation of shearing and compressive forces requires precise assessment of muscle moment arm lengths regarding to instantaneous joint rotation axis during stance phase of gait or running (19). The equation obtained by curve fitting in current model provided a better estimation of further patellar tendon moment arm lengths in knee range of motion.

Furthermore, the results of the present study also reveal the ability of MRI as a noninvasive tool for studying joint and muscle biomechanics. Unlike X-rays, MR images comprise soft tissues, e.g. muscles and tendons, thus the moment arm lengths can be measured directly from these images without making hypothesis as to the tendon actual path (20).

Generally, we concluded that the PTma is impressed by the knee bones shapes and the relative movements of the femur and tibia in 3D images. Decreasing the PTma during knee flexion as shown in this study may be due to the muscle–tendon displacement and knee instantaneous central rotation, caused by muscle thickness changes or malformation of nearly retinacular sheaths and shift of the center of joint rotation as a result of ligament and joint capsule deformation. It can also be affected by some other factors including growth, aging, and level of physical activity. One of the most important limitations of this study was the measuring of PTma in static positions due to lack of facilities. These findings could be a preface for dynamic studies in future by providing equipments such as dynamic MRI. Further studies would be needed to study the effect of anthropometric parameters on moment arm length and also measure moment arm length in patellofemoral pain syndrome as one of the most common musculoskeletal injuries in dynamic functions (21).

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