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In vivo changes in the human patellar tendon moment arm length with different modes and intensities of muscle contraction

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Abstract

The purpose of this study was to examine the effect of different muscle contraction modes and intensities on patellar tendon moment arm length (d_{PT}). Five men performed isokinetic concentric, eccentric and passive knee extensions at an angular velocity of 60 deg/s and six men performed gradually increasing to maximum effort isometric muscle contractions at 90° and 20° of knee flexion. During the tests, lateral X-ray fluoroscopy imaging was used to scan the knee joint. The d_{PT} differences between the passive state and the isokinetic concentric and extension were quantified at 15° intervals of knee joint flexion angle. Furthermore, the changes of the d_{PT} as a function of the isometric muscle contraction intensities were determined during the isometric knee extension at 90° and 20° of knee joint flexion. Muscle contraction-induced changes in knee joint flexion angle during the isometric muscle contraction were also taken into account for the d_{PT} measurements. During the two isometric knee extensions, d_{PT} increased from rest to maximum voluntary muscle contraction (MVC) by 14–15%. However, when changes in knee joint flexion angle induced by the muscle contraction were taken into account, d_{PT} during MVC increased by 6–26% compared with rest. Moreover, d_{PT} increased during concentric and eccentric knee extension by 3–15%, depending on knee flexion angle, compared with passive knee extension. These findings have important implications for estimating musculoskeletal loads using modelling under static and dynamic conditions.
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Keywords: Muscle moment arm; Knee extension; Musculoskeletal modelling

1. Introduction

In human and animal musculoskeletal systems, forces produced by muscle contraction generate joint moments. The joint moment depends on the muscle–tendon force and moment arm length, which is defined as the perpendicular distance from the joint centre/axis of rotation to the muscle–tendon action line (Pandy, 1999; Tsaopoulos et al., 2006). For a given a joint moment, the muscle (and subsequently joint) forces will depend on the moment arm length. Similarly, if a muscle force is calculated by a muscle model then the moment applied to the joint will also depend on the moment arm. Therefore, accurate values of muscle–tendon moment arms are of vital importance for accurate calculation of internal forces using inverse dynamics models and movement simulations using forward dynamics models (Maganaris et al., 2001).

During knee joint extension, the main moment arm affecting joint moment is the patellar tendon moment arm. This is the leverage of the effective force transmitted to the tibia during contraction of the quadriceps muscle. Conventionally, the patellar tendon moment arm length (d_{PT}) has been quantified from measurements on cadaver specimens (Herzog and Read, 1993; Buford et al., 1997; Krevolin et al., 2004), or in vivo measurements using imaging techniques at rest (Smidt, 1973; Nisell et al., 1986; Wretenberg et al., 1996). However, moment arms change with muscle contraction (Maganaris et al., 1998, 1999), and it has long been recognised that moment arms at the time that the load is exerted are required for the realistic estimation of muscle and joint forces (Visser et al., 1990;

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Spoor and van Leeuwen, 1992). Kellis and Baltzopoulos (1999) have used X-ray video fluoroscopy and measured the human d_{PT} during knee extensor muscle contraction against manual resistance applied on the lower leg. This was to ensure that the moment arm was measured under some loading in the joint rather than at complete rest. However, the external resistive forces applied across the range of movement were not measured and, therefore, the moment arm lengths obtained could not be compared with measurements at rest to quantify the effect of muscle contraction. To our knowledge, only Imran et al. (2000) examined the variation in d_{PT} with increasing muscle force. These authors used modelling and reported that a tenfold increase in the quadriceps force during simulated isometric knee extension resulted in a 2% increase of the d_{PT} at 0° of knee flexion. However, the findings reported by Imran et al. (2000) for the d_{PT} changes are limited because the two-dimensional knee joint model used by this study did not account for the elasticity of the patellar tendon. The elastic deformation of the patellar tendon would affect the orientation of the patellar tendon action line and consequently the d_{PT}. Moreover, it should be considered that the d_{PT} during maximum voluntary muscle contraction (MVC) may be different from the moment arms during daily living and other multisegment activities, where concentric and eccentric muscle contractions are normally performed and the forces exerted are different.

In light of the above considerations, the purpose of the present study was to quantify in vivo the effects of muscle contraction intensity and mode (isometric, isokinetic concentric and eccentric knee extensions) on the human patellar tendon moment arm length using X-ray videofluoroscopy.

2. Methods

2.1. Participants

Eleven healthy males (age: 25.3 ± 4.3 years, height: 178.4 ± 5.6 cm, body mass: 72.3 ± 4.7 kg) without any musculoskeletal injuries of the lower limbs volunteered to participate in this study after signing informed consent and radiation risk information forms. The maximum radiation exposure time in this study was limited to 15 s for each participant. This exposure time produces a maximum effective radiation dose that is less than 1.5 μSv based on the X-ray videofluoroscopy system exposure settings used. The experimental procedures were approved by the local ethical committee.

2.2. Procedure

Measurements were taken on the right leg. Knee extension contractions were performed on a Cybex Norm (Cybex, Ronkonkama, New York, U.S.A.) isokinetic dynamometer. The dynamometer was fitted with an extended input arm, to allow an adequate gap (45 cm) between the chair and the main unit to accommodate the image intensifier of a GE FlexiView 8800 C-arm X-ray videofluoroscopy system (Fig. 1). The participants were positioned on the chair and were stabilised with the standard belts and thigh straps. Straps were positioned over the right thigh, at the hip and shoulders to prevent any extraneous movement. Before each knee extension trial, the most prominent point of the femoral epicondyle on the lateral surface of the knee joint and a metal disc on a strip of Perspex glass that was rigidly attached to the chair were aligned with the dynamometer axis of rotation using a special laser pointing device. The alignment was performed at 90° of knee flexion under submaximal muscle contraction conditions. Gravitational corrections were also performed to account for the effect of leg and dynamometer arm weight on moment measurements.

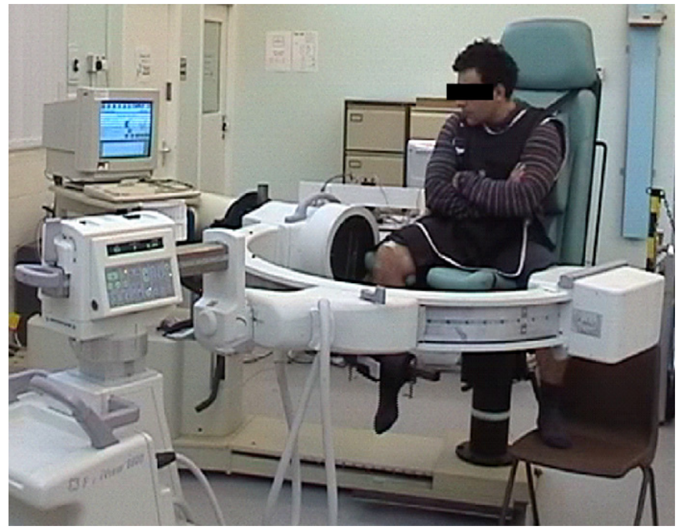

Fig. 1. Photograph of the experimental set-up.

Prior to testing, the image intensifier of the X-ray fluoroscopy system was positioned lateral to the right knee of the participant to enable recording lateral X-ray images of the tibiofemoral joint during the tests. The image intensifier has a 12 in diameter so in the captured knee joint images about 10 cm of the distal femur and the proximal tibia are visible. The X-ray fluoroscopy images were video recorded at 25 Hz, and low dose automatic exposures used.

Due to the nature of the X-ray radiation emitted, the participants were divided into two groups to minimise the radiation exposure time. The first group ($n = 5$) performed maximal concentric and eccentric knee extensions at an angular velocity of 60 deg/s; the participants of the second group ($n = 6$) were instructed to perform maximal isometric knee extensions at 20° and 90° of knee flexion by gradually increasing their effort to the maximum in ~3 s. X-ray images were also recorded in both groups while the scanned knee was passively extended by the dynamometer from 90° to 0° knee flexion. All trials were performed in front of the image intensifier of the X-ray system.

Moment and angular displacement data from the isokinetic dynamometer were recorded with an acquisition system (Acknowledge, Biopac Systems Inc., Santa Barbara, CA, USA) at a sampling frequency of 200 Hz. An external voltage (10 V) trigger was used to synchronise the X-ray system with the analog data acquisition system.

2.3. X-Ray videofluoroscopy analysis

Prior to the determination of all the geometric and kinematic parameters, the geometric pin-cushion and sigmoidal optical distortion of the X-ray images due to the curvature of the image intensifier and the deflection of the electrons inside the image intensifier caused by any external magnetic field, respectively, were corrected using a thin-plate splines method (Fantozzi et al., 2003).

On the X-ray images recorded, the d_{PT} was measured as the perpendicular distance from the tibiofemoral contact point (TFCP) to the patellar tendon action line (Nisell, 1985; Baltzopoulos, 1995; Kellis and Baltzopoulos, 1999; Chow et al., 2006). We chose the TFCP as a reference point for the d_{PT} measurement, because the moment produced by joint contact forces about this point is zero which enables the solution of the moment equilibrium equation about the knee joint for the calculation of patellar tendon forces (Nisell et al., 1986; Kellis and

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