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Article

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The human patellar tendon moment arm assessed in vivo using dual-energy X-ray absorptiometry

Robert M. Erskine[1,2], Christopher I. Morse[1], Stephen H. Day[1], Alun G. Williams[1] and Gladys L. Onambele-Pearson[1]

[1]Institute for Performance Research, Department of Exercise and Sport Science, Manchester Metropolitan University, Crewe, United Kingdom; [2]Research Institute for Sport and Exercise Sciences, Liverpool John Moores University, Liverpool, United Kingdom.

Address for reprint requests and all other correspondence:

R. M. Erskine, School of Sport and Exercise Science, Liverpool John Moores University, Liverpool, L3 3AF, United Kingdom; Telephone: +44 (0)151 904 6256; Fax: +44 (0)151 904 6284; Email: R.M.Erskine@ljmu.ac.uk

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ABSTRACT

Accurate assessment of muscle-tendon forces in vivo requires knowledge of the muscle-tendon moment arm. Dual-energy X-ray absorptiometry (DXA) can produce 2D images suitable for visualising both tendon and bone, thereby potentially allowing the moment arm to be measured but there is currently no validated DXA method for this purpose. The aims of this study were (i) to compare in vivo measurements of the patellar tendon moment arm (d_{PT}) assessed from 2D DXA and magnetic resonance (MR) images and (ii) to compare the reliability of the two methods. Twelve healthy adults (mean±SD: 31.4±9.5 yr; 174.0±9.5 cm; 76.2±16.6 kg) underwent two DXA and two MR scans of the fully extended knee at rest. The tibiofemoral contact point (TFCP) was used as the centre of joint rotation in both techniques, and the d_{PT} was defined as the perpendicular distance from the patellar tendon axis to the TFCP. The d_{PT} was consistently longer when assessed via DXA compared to MRI (+3.79±1.25 mm or +9.78±3.31%; $P<0.001$). The test-retest reliability of the DXA [CV=2.13%; ICC=0.94; ratio limits of agreement (RLA)=1.01 (*/÷1.07)] and MR [(CV=2.27%; ICC=0.96; RLA=1.00 (*/÷1.07)] methods was very high and comparable between techniques. Moreover, the RLA between the mean DXA and MRI d_{PT} values [1.097 (*/÷1.061)] demonstrated very strong agreement between the two methods. In conclusion, highly reproducible d_{PT} measurements can be determined from DXA imaging with the knee fully extended at rest. This has implications for the calculation of patellar tendon forces in vivo where MR equipment is not available.

INTRODUCTION

Calculating the force produced by human muscle in vivo requires knowledge of the joint moment as well as the muscle-tendon moment arm (the internal leverage of the effective muscle force to the bone). In 2D imaging, the patellar tendon moment arm (d_{PT}) is defined as the perpendicular distance from the knee joint axis of rotation to the patellar tendon action line (Baltzopoulos, 1995; Erskine et al., 2009; Tsaopoulos et al., 2007b), and is the main moment arm affecting joint moment during knee extension. As d_{PT} is known to vary between individuals of an homogenous population (Erskine et al., 2009; Tsaopoulos et al., 2007b), accurate measurements of d_{PT} are essential to avoid making erroneous conclusions concerning between subject/group differences in 'muscle strength'.

Both magnetic resonance imaging (MRI) (Erskine et al., 2010; Tsaopoulos et al., 2007b; Wretenberg et al., 1996) and 2D X-ray video fluoroscopy (Baltzopoulos, 1995; Tsaopoulos et al., 2009) have previously been used to measure the human d_{PT} in vivo at rest, and during muscle contraction (Imran et al., 2000; Kellis and Baltzopoulos, 1999; Tsaopoulos et al., 2007a). The d_{PT} has been shown to change as a function of knee joint angle (Baltzopoulos, 1995; Wretenberg et al., 1996) and different reference points for defining the knee joint rotation centre can result in variable d_{PT} values (Tsaopoulos et al., 2009). Moreover, even when the same reference location is used, i.e. the tibiofemoral contact point (TFCP), and a consistent knee joint angle (e.g. full knee extension) in the same population (e.g. young healthy men), in vivo measurements of d_{PT} have been shown to differ considerably between studies (Baltzopoulos, 1995; Erskine et al., 2009; Tsaopoulos et al., 2007a; Tsaopoulos et al., 2007b; Wretenberg et al., 1996). Given the otherwise similar methodology of these previous studies, it is possible that the disparity in reported d_{PT} values could be due to the different imaging techniques used, i.e. MRI as opposed to X-ray. However, to our knowledge, no study has directly compared these two techniques for assessing d_{PT} in vivo. Thus, a direct comparison between MRI and X-ray image-derived calculations of d_{PT} (providing a scaling factor for any measurement differences) is essential if results between studies are to be reliably compared.

Due to its ability to accurately differentiate between tissues of different densities, dual-energy X-ray absorptiometry (DXA) has become the gold standard assessment of body composition (Kamimura et al., 2003a; Kamimura et al., 2003b; Kohrt, 1998; Prior et al., 1997). Consequently, DXA is increasingly being used to measure changes in body composition following interventions designed to increase muscle mass and strength (Burk et al., 2009; Burke et al., 2001; Hartman et al., 2007; Josse et al., 2010; Kerksick et al., 2006). In these studies, maximum quadriceps muscle strength was assessed either as the knee joint moment or the maximal load that could be lifted during one repetition of the knee extension training task. However, without knowledge of the d_{PT} [and the level of antagonist muscle co-activation (Erskine et al., 2009; Erskine et al., 2010; Macaluso et al., 2002; Reeves et al., 2004a)], neither of these indices of strength can be used to accurately determine the force produced by the quadriceps muscle. Such a limitation increases the probability of erroneous study conclusions.

We hypothesised that the quality of short duration, (~10 s), low radiation (Damilakis et al., 2010) instant vertebral assessment (IVA) DXA scans would be high enough to determine d_{PT} in vivo. To our knowledge, the only reports of DXA-derived ‘moment arm’ measurements relate to spinal muscle moment arms (Duan et al., 2001) or hip axis lengths

(Cummings et al., 1994; Faulkner et al., 1993; Faulkner et al., 1995); as yet there are no reports of d_{PT} measured using DXA. However, any novel method for assessing d_{PT} in vivo should be validated against a recognised technique, such as MRI (Erskine et al., 2010; Onambele-Pearson and Pearson, 2012; Tsaopoulos et al., 2007b).

The main aim of this study was to compare the resting in vivo assessment of d_{PT} using 2D DXA and MR imaging techniques with the knee fully extended and the TFCP used as the reference point for the centre of joint rotation in both cases. A second aim was to compare the reliability of these two methods. We hypothesised that the reliability of the two protocols would be high as well as comparable and that the two techniques would be in strong agreement.

METHODS

Participants

Twelve healthy adults (8 male, 4 female) provided written informed consent prior to participation in this study, which complied with the Declaration of Helsinki and was approved by the local ethics committee of Manchester Metropolitan University. Age, stature and body mass (mean ± SD) were 31.4 ± 9.5 yr, 174.0 ± 9.5 cm, and 76.2 ± 16.6 kg, respectively. Exclusion criteria included history of either knee joint/patellar tendon disorders or knee surgery; pregnancy (relating to the DXA scan).

Experimental design

Participants were required to undergo scanning of the right knee on two occasions using a 0.25-T G-Scan MRI scanner (Esaote Biomedica, Genoa, Italy) and two more occasions using a Discovery W DXA scanner (Hologic Inc., Bedford, USA). During the scans, participants wore a pair of shorts to provide easy access to the knee and all scans were taken at rest with the knee joint fully extended.

Scanning protocols

For the MRI session, participants were instructed to remain relaxed and still in the supine position for the duration of the sagittal knee scan. A 'turbo 3D T1-weighted' sequence was used with the following scanning parameters: time of repetition 40 ms; time to echo 16 ms; matrix 256 x 256; field of view 180 mm x 180 mm; slice thickness 3.4 mm; interslice gap 0 mm. The procedure was then repeated to calculate the test-retest reliability (in between scans, participants were removed from the MRI scanner). For the DXA session, an 'Instant Vertebral Assessment in High Definition' (IVA-HD) scan was taken of the knee using the following parameters: scan length = 20.3 cm; scan width 13.7 cm; line spacing = 0.0241 cm; point resolution = 0.1086 cm; scanning time = 11 s; radiation exposure = 0.025 mGy. To gain a single sagittal image of the knee, the joint was scanned with the lateral aspect of the limb placed on the scanning bed and the knee (set to 0° knee flexion) placed within the imaging zone. The procedure was then repeated to calculate the test-retest reliability (participants were removed from the scanner in between DXA scans).

Image analysis

To enable accurate identification of the contact points between the tibial plateau and the medial and lateral femoral condyles, the turbo 3D MRI scan was reconstructed offline in the coronal plane using the same parameters as used for the 'slices' in the sagittal plane (see below for details). All dicom images (from both the MRI and DXA scans) were subsequently imported to a dicom viewer (Osirix 2.7.5, Osirix Foundation, Geneva, Switzerland) for image analysis. For both the DXA and MRI methods, the d_{PT} was then calculated with reference to the tibiofemoral contact point (TFCP), i.e. the midpoint of the shortest distance between the lateral and medial femoral condyles and the tibial plateau (Baltzopoulos, 1995; Wretenberg et al., 1996). For the MRI scan, the coronal plane images were used to identify the appropriate sagittal images that would be used to locate the TFCP, i.e. the two images displaying the least distance (measured using Osirix) between the tibial plateau and the lateral and medial femoral condyles (the lateral and medial CPs), as previously described (Tsaopoulos et al., 2007b; Wretenberg et al., 1996). The mean X, Y, Z coordinates of these CPs were used to locate the TFCP on the central sagittal image (Fig. 1A), i.e. the sagittal image midway between the sagittal images of the lateral and medial CPs. Thus, three 2D (sagittal) 'slices' were selected from the whole MRI sagittal slice sequence: two to locate the lateral and medial CPs and the third (central image) clearly showing the patella apex, the patellar tendon and cruciate ligaments, which was used to measure d_{PT}. For the single 2D DXA dicom image obtained, the TFCP was located from the single sagittal dicom image, as previously described using 2D X-ray video fluoroscopy (Baltzopoulos, 1995; Kellis and Baltzopoulos, 1999; Tsaopoulos et al., 2007a). From this image, the lateral and medial CPs were easily identified, together with the patellar tendon, the patella apex and the tibial tuberosity (Fig. 1B). The TFCP was located and marked on both the central sagittal MR image and the DXA image using the appropriate software (Osirix Foundation), and the axis of the patellar tendon was defined by a straight line drawn through the centre of the tendon, from the patella apex to the tibial tuberosity (Fig. 1).

The d_{PT} was then defined as the length of the perpendicular distance between the patellar tendon action line and the TFCP (Tsaopoulos et al., 2007b).

Insert Fig. 1 near here.

Statistical analysis

All measurements and data analyses were performed by the same investigator. The test-retest reliability of both the MRI and DXA d_{PT} assessments was determined by calculating the coefficient of variation (CV), intraclass correlation coefficient (ICC, model: 2-way mixed; type: absolute agreement), and the ratio limits of agreement (Nevill and Atkinson, 1997) of the repeated measurements for each method. The mean d_{PT} from the two MRI scans and from the two DXA scans was calculated for each participant and the ratio limits of agreement were calculated to determine the level of agreement between the two methods. Statistical significance was accepted when $P < 0.05$ and all data are presented as means ± SD unless otherwise stated.

RESULTS

DXA-derived d_{PT} values were consistently higher (+9.78 ± 3.31%, i.e. +3.79 ± 1.25 mm) than those determined from the established MRI method (paired t-test, $P < 0.001$; Table 1). The test-retest reliability of both the DXA and MRI methods was very high and extremely comparable between methods, as demonstrated by the low CVs, high ICCs (with narrow 95% confidence intervals) and close ratio limits of agreement (Table 1). Regarding the agreement between the DXA and MRI-based methods, the ratio limits of agreement were 1.097 (*/÷ 1.061) (Fig. 2). The bias ratio (1.097) implies that DXA-derived d_{PT} measurements were on average 9.7% higher than those determined using the established MRI method (thus agreeing with the mean difference between methods), while the agreement ratio (*/÷ 1.061) indicates that 95% of the agreement ratios lay within 6.1% above or below the mean bias ratio, i.e. between a lower limit of agreement of 1.097/1.061 = 1.034 and an upper limit of agreement of 1.097*1.061 = 1.164. Thus, it could be stated with 95% certainty that DXA d_{PT} measurements were between 3.4% and 16.4% larger than MRI-derived values. Furthermore, there was no relationship between the absolute error (difference between DXA and MRI d_{PT} measurements) and the mean [(DXA+MRI)/2] d_{PT} (absolute data: $r = 0.208$; $P = 0.517$; log transformed data: $r = 0.004$; $P = 0.991$). Together with the tight ratio limits of agreement (presented above), this demonstrates the homoscedasticity of the data, i.e. the between method difference was not dependent upon d_{PT}. This was illustrated by the consistent difference between DXA and MRI-derived d_{PT} values (Fig. 2).

Insert Table 1 near here.

Insert Fig. 2 near here.

DISCUSSION

The main aim of this study was to compare 2D resting DXA vs. MRI measurements of d_{PT} obtained in vivo at the same joint angle (full knee extension), and using the same reference point as the centre of joint rotation (the tibiofemoral contact point, or TFCP). To our knowledge, this is the first report to directly compare d_{PT} assessed via DXA and MRI, and we found that DXA-derived measurements of d_{PT} overestimated MRI d_{PT} values by 9.7 ± 3.3%. Moreover, due to the consistent difference between methods, we have shown that the two techniques were in strong agreement, regardless of inter-individual differences in knee joint dimensions. Our second aim was to determine the test-retest reliability of each method, and we have shown that both techniques were highly reproducible and to a similar extent. Thus, we have shown for the first time that DXA imaging enables a valid and reliable measure of d_{PT}.

In this study, we used a high definition IVA DXA protocol to obtain a single high quality 2D sagittal image of the resting, fully extended knee, from which the medial and lateral femoral condyles, tibial plateau, patella apex, tibial tuberosity and patellar tendon were all clearly visible (Fig. 1B). Thus, it was possible to measure the d_{PT}, i.e. the perpendicular distance from the patellar tendon action line to the tibiofemoral contact point (TFCP, the midpoint of the shortest distance between the two femoral condyles and the tibia plateau), a technique that has been previously described using 2D X-ray video fluoroscopy (Baltzopoulos, 1995; Kellis and Baltzopoulos, 1999; Tsaopoulos et al., 2007a). Using the same participants, we then directly compared DXA-derived measurements of d_{PT} with values obtained from a commonly reported method using 2D MR images (Erskine et al., 2010; Onambele-Pearson and Pearson, 2012; Tsaopoulos et al., 2007b) of the fully extended knee at rest, again using the TFCP as the centre of joint rotation (Fig. 1A). The 42.7 ± 3.9 mm (DXA) and 38.9 ± 3.7 mm (MRI) in vivo d_{PT} values reported here were similar to those reported previously using the TFCP technique from X-ray (Baltzopoulos, 1995; Chow et al., 2006; Kellis and Baltzopoulos, 1999) and MRI (Erskine et al., 2010; Tsaopoulos et al., 2007b; Wretenberg et al., 1996) images. One explanation for the 9.7% difference in d_{PT} values obtained from our two methods could be related to the DXA method relying on a single sagittal image containing an ‘average’ view of the whole knee in that plane, while the MRI method enables the knee to be viewed in multiple ‘slices’ in both the sagittal and coronal planes. The TFCP was located consistently further from the patellar tendon action line in the DXA scan compared to when the TFCP was located using a combination of both coronal and sagittal MR slices (although d_{PT} was measured from the single, central sagittal image), thus overestimating d_{PT} by 9.7%. However, not only was the variance between the two techniques consistent (Fig. 2), but the d_{PT} values obtained from the two methods were found to be in strong agreement, as demonstrated by the close ratio limits of agreement.

Although leading to a relatively small difference in absolute d_{PT} values, the 9.7% bias ratio reported here would have relatively large implications for the calculation of quadriceps femoris muscle force resolved at the patellar tendon in this population. For example, the patellar tendon force for a healthy young man or woman with a knee extension moment of 200 N·m and a d_{PT} of 45 mm (as assessed via MRI) would be ~4,444 N. However, if d_{PT} had been determined via DXA, the tendon force would be calculated as ~4,051 N, a difference of ~393 N. Thus, a consistent ratio bias (÷1.097) may be applied to DXA d_{PT} measurements in healthy, young men and women (obtained using the novel method described here), to provide values comparable with MRI studies. We acknowledge, however, that further work is required in different populations before a universal correction factor may be applied. Furthermore, with the increasing use of DXA in studies designed to determine the effect of interventions on muscle mass and strength (Burk et al., 2009; Burke et al., 2001; Hartman et al., 2007; Josse et al., 2010; Kerksick et al., 2006), it would be beneficial to use DXA to help determine muscle-tendon forces to prevent erroneous conclusions regarding between group differences and/or training-induced changes in 'muscle strength'. This could occur due to inter-individual differences in d_{PT} (Erskine et al., 2009; Tsaopoulos et al., 2007b) and differences/changes in the optimal knee joint angle for peak force production [thus affecting d_{PT} (Baltzopoulos, 1995; Wretenberg et al., 1996)] due to differences/changes in muscle fascicle length and/or tendon stiffness (Reeves et al., 2004b).

We have shown here that the test-retest reproducibility of the DXA d_{PT} assessment was not only high (CV of 2.1%; ICC of 0.94; RLA of 1.01 (*/÷ 1.07); Table 1) but was similar to that of the recognized MRI technique (CV of 2.3%; ICC of 0.96; RLA of 1.00 (*/÷ 1.07); Table 1), thus demonstrating the validity of the DXA method. Previously, the digitizing process for calculating d_{PT} from 2D X-ray video fluoroscopy has been reported as having a very high reliability (CV of 1.23%) (Baltzopoulos, 1995) but to our knowledge, test-retest reproducibility of the entire d_{PT} assessment from X-ray images (including multiple scans of the same knees) has not been reported. This could be due to the high radiation emitted during a standard radiograph compared to the low effective dose during an IVA DXA scan (Damilakis et al., 2010). Therefore, not only does this study demonstrate the high reproducibility of the entire 2D assessment of d_{PT} via DXA at rest, but it reflects the high reliability of identifying the correct anatomical landmarks, i.e. the medial and lateral tibiofemoral contact points, patella apex and the tibial tuberosity, on multiple occasions from a single X-ray image (Baltzopoulos, 1995; Chow et al., 2006; Kellis and Baltzopoulos, 1999). Using 2D MRI scans to identify the geometric centre of the femoral condyles (GCFC) as the reference point for the centre of rotation, other investigators have reported the typical error, which provides an indication of the test-retest reliability, as 0.5 mm (O'Brien et al., 2009). This value was comparable to the 0.9 mm and 1.0 mm for our MRI and DXA methods, respectively (data not reported). Thus, the reliability of our novel DXA method for determining d_{PT} was comparable not only to the TFCP MRI method reported in our study, but also to a different method incorporating 2D MR images and the GCFC reference point for the centre of knee joint rotation (O'Brien et al., 2009).

Recently, quadriceps muscle-tendon moment arms have been measured in 3D during dynamic rotation (Westphal et al., 2013; Wilson and Sheehan, 2009) and it has been shown that Achilles tendon moment arm values are overestimated when analysed in 2D compared with 3D (Hashizume et al., 2012). Thus, future studies should examine whether this is also the case for d_{PT}, and whether this has any implications for our findings. Furthermore, d_{PT} measured in 2D changes as a function of knee joint angle (Baltzopoulos, 1995; Tsaopoulos et al., 2009; Wretenberg et al., 1996) and of isometric (Tsaopoulos et al., 2007a) and dynamic (Imran et al., 2000) muscle contraction intensity. Therefore, it is not known whether assessing d_{PT} at multiple joint angles or during muscle contraction would have influenced the test-retest reliability of both methods, or indeed the comparison of d_{PT} between methods in our study. However, as d_{PT} changes with knee angle in a similar manner when assessed via 2D X-ray video fluoroscopy (Baltzopoulos, 1995) and MRI (Wretenberg et al., 1996) using the TFCP as the reference point of joint rotation, we maintain that this technical compromise did not invalidate our comparative findings.

Conclusion

We have shown for the first time that reliable d_{PT} measurements can be determined from a single, high quality, short duration DXA scan. For the fully extended knee at rest, this novel method generates consistently (9.7%) longer d_{PT} values and demonstrates equally high reproducibility when compared to an established MRI technique. Thus, d_{PT} measurements obtained from DXA images may be used to help calculate muscle-tendon forces in vivo.

Conflict of interest

The authors declare no conflict of interest.

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Table

Table 1. The test-retest reliability of the patellar tendon moment arm (d_{PT}) measured using knee scans obtained from a dual-energy X-ray absorptiometry (DXA) and a magnetic resonance imaging (MRI) scanner. Values for d_{PT} are mean ± SD.

	DXA	**MRI**
d_{PT} (mm)	42.70 ± 3.93	38.91 ± 3.67
CV (%)	2.13	2.27
ICC (lower CL – upper CL)	0.97 (0.91 – 0.99)	0.98 (0.93 – 0.99)
RLA (test 2 – test 1)	1.01 (*/÷ 1.07)	1.00 (*/÷ 1.07)

CV, coefficient of variation; ICC, intraclass correlation coefficient; CL, 95% confidence limit; RLA, ratio limits of agreement.

Figure legends

Figure 1. Representative images from the MRI (A) and DXA (B) assessments of d_{PT} in the same participant; P, patella; F, femur; T, tibia; TFCP, tibiofemoral contact point; PT, patellar tendon; d_{PT}, patellar tendon moment arm.

Figure 2. The bias ratio (1.097, solid line; $r = 0.948$; $P < 0.001$) and ratio limits of agreement (upper = 1.164, lower = 1.034, dashed lines) between the MRI and DXA imaging methods used to calculate d_{PT}; dotted line = line of identity; n = 12.