



## LJMU Research Online

**Erskine, RM, Morse, CI, Day, SH, Williams, AG and Onambele-Pearson, GL**

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

<http://researchonline.ljmu.ac.uk/id/eprint/2991/>

### Article

**Citation** (please note it is advisable to refer to the publisher's version if you intend to cite from this work)

**Erskine, RM, Morse, CI, Day, SH, Williams, AG and Onambele-Pearson, GL (2014) The human patellar tendon moment arm assessed in vivo using dual-energy X-ray absorptiometry. Journal of Biomechanics, 47 (6). pp. 1294-1298. ISSN 0021-9290**

LJMU has developed **LJMU Research Online** for users to access the research output of the University more effectively. Copyright © and Moral Rights for the papers on this site are retained by the individual authors and/or other copyright owners. Users may download and/or print one copy of any article(s) in LJMU Research Online to facilitate their private study or for non-commercial research. You may not engage in further distribution of the material or use it for any profit-making activities or any commercial gain.

The version presented here may differ from the published version or from the version of the record. Please see the repository URL above for details on accessing the published version and note that access may require a subscription.

For more information please contact [researchonline@ljmu.ac.uk](mailto:researchonline@ljmu.ac.uk)

<http://researchonline.ljmu.ac.uk/>

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

Robert M. Erskine<sup>1,2</sup>, Christopher I. Morse<sup>1</sup>, Stephen H. Day<sup>1</sup>, Alun G. Williams<sup>1</sup> and Gladys L. Onambele-Pearson<sup>1</sup>

<sup>1</sup>*Institute for Performance Research, Department of Exercise and Sport Science, Manchester Metropolitan University, Crewe, United Kingdom;* <sup>2</sup>*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

**Running title:** DXA measurements of patellar tendon moment arm

**Key words:** patellar tendon; moment arm; dual-energy X-ray absorptiometry (DXA); magnetic resonance imaging (MRI).

**This is an original article.**

**Word count:** 3,215

## 2 ABSTRACT

3 Accurate assessment of muscle-tendon forces *in vivo* requires knowledge of the muscle-  
4 tendon moment arm. Dual-energy X-ray absorptiometry (DXA) can produce 2D images  
5 suitable for visualising both tendon and bone, thereby potentially allowing the moment  
6 arm to be measured but there is currently no validated DXA method for this purpose. The  
7 aims of this study were (i) to compare *in vivo* measurements of the patellar tendon  
8 moment arm ( $d_{PT}$ ) assessed from 2D DXA and magnetic resonance (MR) images and (ii)  
9 to compare the reliability of the two methods. Twelve healthy adults (mean $\pm$ SD:  
10 31.4 $\pm$ 9.5 yr; 174.0 $\pm$ 9.5 cm; 76.2 $\pm$ 16.6 kg) underwent two DXA and two MR scans of  
11 the fully extended knee at rest. The tibiofemoral contact point (TFCP) was used as the  
12 centre of joint rotation in both techniques, and the  $d_{PT}$  was defined as the perpendicular  
13 distance from the patellar tendon axis to the TFCP. The  $d_{PT}$  was consistently longer  
14 when assessed via DXA compared to MRI (+3.79 $\pm$ 1.25 mm or +9.78 $\pm$ 3.31%;  $P<0.001$ ).  
15 The test-retest reliability of the DXA [CV=2.13%; ICC=0.94; ratio limits of agreement  
16 (RLA)=1.01 (\*/ $\div$ 1.07)] and MR [(CV=2.27%; ICC=0.96; RLA=1.00 (\*/ $\div$ 1.07)]  
17 methods was very high and comparable between techniques. Moreover, the RLA  
18 between the mean DXA and MRI  $d_{PT}$  values [1.097 (\*/ $\div$ 1.061)] demonstrated very  
19 strong agreement between the two methods. In conclusion, highly reproducible  $d_{PT}$   
20 measurements can be determined from DXA imaging with the knee fully extended at  
21 rest. This has implications for the calculation of patellar tendon forces *in vivo* where  
22 MR equipment is not available.

23

## 24 INTRODUCTION

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

34

35 Both magnetic resonance imaging (MRI) (Erskine et al., 2010; Tsaopoulos et al., 2007b;  
36 Wretenberg et al., 1996) and 2D X-ray video fluoroscopy (Baltzopoulos, 1995; Tsaopoulos  
37 et al., 2009) have previously been used to measure the human  $d_{PT}$  *in vivo* at rest, and  
38 during muscle contraction (Imran et al., 2000; Kellis and Baltzopoulos, 1999; Tsaopoulos  
39 et al., 2007a). The  $d_{PT}$  has been shown to change as a function of knee joint angle  
40 (Baltzopoulos, 1995; Wretenberg et al., 1996) and different reference points for  
41 defining the knee joint rotation centre can result in variable  $d_{PT}$  values (Tsaopoulos et al.,  
42 2009). Moreover, even when the same reference location is used, i.e. the tibiofemoral  
43 contact point (TFCP), and a consistent knee joint angle (e.g. full knee extension) in the  
44 same population (e.g. young healthy men), *in vivo* measurements of  $d_{PT}$  have been  
45 shown to differ considerably between studies (Baltzopoulos, 1995; Erskine et al., 2009;  
46 Tsaopoulos et al., 2007a; Tsaopoulos et al., 2007b; Wretenberg et al., 1996). Given the  
47 otherwise similar methodology of these previous studies, it is possible that the disparity

48 in reported  $d_{PT}$  values could be due to the different imaging techniques used, i.e. MRI as  
49 opposed to X-ray. However, to our knowledge, no study has directly compared these  
50 two techniques for assessing  $d_{PT}$  *in vivo*. Thus, a direct comparison between MRI and X-  
51 ray image-derived calculations of  $d_{PT}$  (providing a scaling factor for any measurement  
52 differences) is essential if results between studies are to be reliably compared.

53

54 Due to its ability to accurately differentiate between tissues of different densities, dual-  
55 energy X-ray absorptiometry (DXA) has become the gold standard assessment of body  
56 composition (Kamimura et al., 2003a; Kamimura et al., 2003b; Kohrt, 1998; Prior et al.,  
57 1997). Consequently, DXA is increasingly being used to measure changes in body  
58 composition following interventions designed to increase muscle mass and strength (Burk  
59 et al., 2009; Burke et al., 2001; Hartman et al., 2007; Josse et al., 2010; Kerksick et al.,  
60 2006). In these studies, maximum quadriceps muscle strength was assessed either as the  
61 knee joint moment or the maximal load that could be lifted during one repetition of the  
62 knee extension training task. However, without knowledge of the  $d_{PT}$  [and the level of  
63 antagonist muscle co-activation (Erskine et al., 2009; Erskine et al., 2010; Macaluso et al.,  
64 2002; Reeves et al., 2004a)], neither of these indices of strength can be used to accurately  
65 determine the force produced by the quadriceps muscle. Such a limitation increases the  
66 probability of erroneous study conclusions.

67

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

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

76

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

83

## 84 **METHODS**

### 85 **Participants**

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

92

### 93 **Experimental design**

94 Participants were required to undergo scanning of the right knee on two occasions using  
95 a 0.25-T G-Scan MRI scanner (Esaote Biomedica, Genoa, Italy) and two more

96 occasions using a Discovery W DXA scanner (Hologic Inc., Bedford, USA). During the  
97 scans, participants wore a pair of shorts to provide easy access to the knee and all scans  
98 were taken at rest with the knee joint fully extended.

99

#### 100 *Scanning protocols*

101 For the MRI session, participants were instructed to remain relaxed and still in the  
102 supine position for the duration of the sagittal knee scan. A ‘turbo 3D T1-weighted’  
103 sequence was used with the following scanning parameters: time of repetition 40 ms;  
104 time to echo 16 ms; matrix 256 x 256; field of view 180 mm x 180 mm; slice thickness  
105 3.4 mm; interslice gap 0 mm. The procedure was then repeated to calculate the test-  
106 retest reliability (in between scans, participants were removed from the MRI scanner).

107 For the DXA session, an ‘Instant Vertebral Assessment in High Definition’ (IVA-HD)  
108 scan was taken of the knee using the following parameters: scan length = 20.3 cm; scan  
109 width 13.7 cm; line spacing = 0.0241 cm; point resolution = 0.1086 cm; scanning time  
110 = 11 s; radiation exposure = 0.025 mGy. To gain a single sagittal image of the knee, the  
111 joint was scanned with the lateral aspect of the limb placed on the scanning bed and the  
112 knee (set to 0° knee flexion) placed within the imaging zone. The procedure was then  
113 repeated to calculate the test-retest reliability (participants were removed from the  
114 scanner in between DXA scans).

115

#### 116 *Image analysis*

117 To enable accurate identification of the contact points between the tibial plateau and the  
118 medial and lateral femoral condyles, the turbo 3D MRI scan was reconstructed offline  
119 in the coronal plane using the same parameters as used for the ‘slices’ in the sagittal

120 plane (see below for details). All dicom images (from both the MRI and DXA scans)  
121 were subsequently imported to a dicom viewer (Osirix 2.7.5, Osirix Foundation,  
122 Geneva, Switzerland) for image analysis. For both the DXA and MRI methods, the  $d_{PT}$   
123 was then calculated with reference to the tibiofemoral contact point (TFCP), i.e. the  
124 midpoint of the shortest distance between the lateral and medial femoral condyles and  
125 the tibial plateau (Baltzopoulos, 1995; Wretenberg et al., 1996). For the MRI scan, the  
126 coronal plane images were used to identify the appropriate sagittal images that would be  
127 used to locate the TFCP, i.e. the two images displaying the least distance (measured  
128 using Osirix) between the tibial plateau and the lateral and medial femoral condyles (the  
129 lateral and medial CPs), as previously described (Tsaopoulos et al., 2007b; Wretenberg  
130 et al., 1996). The mean X, Y, Z coordinates of these CPs were used to locate the TFCP  
131 on the central sagittal image (Fig. 1A), i.e. the sagittal image midway between the  
132 sagittal images of the lateral and medial CPs. Thus, three 2D (sagittal) ‘slices’ were  
133 selected from the whole MRI sagittal slice sequence: two to locate the lateral and  
134 medial CPs and the third (central image) clearly showing the patella apex, the patellar  
135 tendon and cruciate ligaments, which was used to measure  $d_{PT}$ . For the single 2D DXA  
136 dicom image obtained, the TFCP was located from the single sagittal dicom image, as  
137 previously described using 2D X-ray video fluoroscopy (Baltzopoulos, 1995; Kellis and  
138 Baltzopoulos, 1999; Tsaopoulos et al., 2007a). From this image, the lateral and medial  
139 CPs were easily identified, together with the patellar tendon, the patella apex and the  
140 tibial tuberosity (Fig. 1B). The TFCP was located and marked on both the central  
141 sagittal MR image and the DXA image using the appropriate software (Osirix  
142 Foundation), and the axis of the patellar tendon was defined by a straight line drawn  
143 through the centre of the tendon, from the patella apex to the tibial tuberosity (Fig. 1).



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

146

147 *Insert Fig. 1 near here.*

148

### 149 **Statistical analysis**

150 All measurements and data analyses were performed by the same investigator. The test-  
151 retest reliability of both the MRI and DXA  $d_{PT}$  assessments was determined by  
152 calculating the coefficient of variation (CV), intraclass correlation coefficient (ICC,  
153 model: 2-way mixed; type: absolute agreement), and the ratio limits of agreement  
154 (Nevill and Atkinson, 1997) of the repeated measurements for each method. The mean  
155  $d_{PT}$  from the two MRI scans and from the two DXA scans was calculated for each  
156 participant and the ratio limits of agreement were calculated to determine the level of  
157 agreement between the two methods. Statistical significance was accepted when  $P <$   
158 0.05 and all data are presented as means  $\pm$  SD unless otherwise stated.

159

### 160 **RESULTS**

161 DXA-derived  $d_{PT}$  values were consistently higher ( $+9.78 \pm 3.31\%$ , i.e.  $+3.79 \pm 1.25$   
162 mm) than those determined from the established MRI method (paired  $t$ -test,  $P < 0.001$ ;  
163 Table 1). The test-retest reliability of both the DXA and MRI methods was very high  
164 and extremely comparable between methods, as demonstrated by the low CVs, high  
165 ICCs (with narrow 95% confidence intervals) and close ratio limits of agreement (Table  
166 1). Regarding the agreement between the DXA and MRI-based methods, the ratio limits  
167 of agreement were 1.097 ( $*/\div 1.061$ ) (Fig. 2). The bias ratio (1.097) implies that DXA-

168 derived  $d_{PT}$  measurements were on average 9.7% higher than those determined using the  
169 established MRI method (thus agreeing with the mean difference between methods),  
170 while the agreement ratio ( $*/\div 1.061$ ) indicates that 95% of the agreement ratios lay  
171 within 6.1% above or below the mean bias ratio, i.e. between a lower limit of agreement  
172 of  $1.097/1.061 = 1.034$  and an upper limit of agreement of  $1.097*1.061 = 1.164$ . Thus,  
173 it could be stated with 95% certainty that DXA  $d_{PT}$  measurements were between 3.4%  
174 and 16.4% larger than MRI-derived values. Furthermore, there was no relationship  
175 between the absolute error (difference between DXA and MRI  $d_{PT}$  measurements) and  
176 the mean  $[(DXA+MRI)/2]$   $d_{PT}$  (absolute data:  $r = 0.208$ ;  $P = 0.517$ ; log transformed  
177 data:  $r = 0.004$ ;  $P = 0.991$ ). Together with the tight ratio limits of agreement (presented  
178 above), this demonstrates the homoscedasticity of the data, i.e. the between method  
179 difference was not dependent upon  $d_{PT}$ . This was illustrated by the consistent difference  
180 between DXA and MRI-derived  $d_{PT}$  values (Fig. 2).

181

182 *Insert Table 1 near here.*

183 *Insert Fig. 2 near here.*

184

## 185 **DISCUSSION**

186 The main aim of this study was to compare 2D resting DXA vs. MRI measurements of  
187  $d_{PT}$  obtained *in vivo* at the same joint angle (full knee extension), and using the same  
188 reference point as the centre of joint rotation (the tibiofemoral contact point, or TFCP).  
189 To our knowledge, this is the first report to directly compare  $d_{PT}$  assessed via DXA and  
190 MRI, and we found that DXA-derived measurements of  $d_{PT}$  overestimated MRI  $d_{PT}$   
191 values by  $9.7 \pm 3.3\%$ . Moreover, due to the consistent difference between methods, we

192 have shown that the two techniques were in strong agreement, regardless of inter-  
193 individual differences in knee joint dimensions. Our second aim was to determine the  
194 test-retest reliability of each method, and we have shown that both techniques were  
195 highly reproducible and to a similar extent. Thus, we have shown for the first time that  
196 DXA imaging enables a valid and reliable measure of  $d_{PT}$ .

197

198 In this study, we used a high definition IVA DXA protocol to obtain a single high  
199 quality 2D sagittal image of the resting, fully extended knee, from which the medial and  
200 lateral femoral condyles, tibial plateau, patella apex, tibial tuberosity and patellar tendon  
201 were all clearly visible (Fig. 1B). Thus, it was possible to measure the  $d_{PT}$ , i.e. the  
202 perpendicular distance from the patellar tendon action line to the tibiofemoral contact  
203 point (TFCP, the midpoint of the shortest distance between the two femoral condyles  
204 and the tibia plateau), a technique that has been previously described using 2D X-ray  
205 video fluoroscopy (Baltzopoulos, 1995; Kellis and Baltzopoulos, 1999; Tsaopoulos et  
206 al., 2007a). Using the same participants, we then directly compared DXA-derived  
207 measurements of  $d_{PT}$  with values obtained from a commonly reported method using 2D  
208 MR images (Erskine et al., 2010; Onambele-Pearson and Pearson, 2012; Tsaopoulos et al.,  
209 2007b) of the fully extended knee at rest, again using the TFCP as the centre of joint  
210 rotation (Fig. 1A). The  $42.7 \pm 3.9$  mm (DXA) and  $38.9 \pm 3.7$  mm (MRI) *in vivo*  $d_{PT}$   
211 values reported here were similar to those reported previously using the TFCP  
212 technique from X-ray (Baltzopoulos, 1995; Chow et al., 2006; Kellis and Baltzopoulos,  
213 1999) and MRI (Erskine et al., 2010; Tsaopoulos et al., 2007b; Wretenberg et al., 1996)  
214 images. One explanation for the 9.7% difference in  $d_{PT}$  values obtained from our two  
215 methods could be related to the DXA method relying on a single sagittal image

216 containing an ‘average’ view of the whole knee in that plane, while the MRI method  
217 enables the knee to be viewed in multiple ‘slices’ in both the sagittal and coronal planes.  
218 The TFCP was located consistently further from the patellar tendon action line in the  
219 DXA scan compared to when the TFCP was located using a combination of both  
220 coronal and sagittal MR slices (although  $d_{PT}$  was measured from the single, central  
221 sagittal image), thus overestimating  $d_{PT}$  by 9.7%. However, not only was the variance  
222 between the two techniques consistent (Fig. 2), but the  $d_{PT}$  values obtained from the two  
223 methods were found to be in strong agreement, as demonstrated by the close ratio limits  
224 of agreement.

225

226 Although leading to a relatively small difference in absolute  $d_{PT}$  values, the 9.7% bias  
227 ratio reported here would have relatively large implications for the calculation of  
228 quadriceps femoris muscle force resolved at the patellar tendon in this population. For  
229 example, the patellar tendon force for a healthy young man or woman with a knee  
230 extension moment of 200 N·m and a  $d_{PT}$  of 45 mm (as assessed via MRI) would be  
231 ~4,444 N. However, if  $d_{PT}$  had been determined via DXA, the tendon force would be  
232 calculated as ~4,051 N, a difference of ~393 N. Thus, a consistent ratio bias ( $\div 1.097$ )  
233 may be applied to DXA  $d_{PT}$  measurements in healthy, young men and women (obtained  
234 using the novel method described here), to provide values comparable with MRI  
235 studies. We acknowledge, however, that further work is required in different  
236 populations before a universal correction factor may be applied. Furthermore, with the  
237 increasing use of DXA in studies designed to determine the effect of interventions on  
238 muscle mass and strength (Burk et al., 2009; Burke et al., 2001; Hartman et al., 2007;  
239 Josse et al., 2010; Kerksick et al., 2006), it would be beneficial to use DXA to help

240 determine muscle-tendon forces to prevent erroneous conclusions regarding between  
241 group differences and/or training-induced changes in ‘muscle strength’. This could  
242 occur due to inter-individual differences in  $d_{PT}$  (Erskine et al., 2009; Tsaopoulos et al.,  
243 2007b) and differences/changes in the optimal knee joint angle for peak force  
244 production [thus affecting  $d_{PT}$  (Baltzopoulos, 1995; Wretenberg et al., 1996)] due to  
245 differences/changes in muscle fascicle length and/or tendon stiffness (Reeves et al.,  
246 2004b).

247

248 We have shown here that the test-retest reproducibility of the DXA  $d_{PT}$  assessment was  
249 not only high (CV of 2.1%; ICC of 0.94; RLA of 1.01 ( $*/\div$  1.07); Table 1) but was  
250 similar to that of the recognized MRI technique (CV of 2.3%; ICC of 0.96; RLA of 1.00  
251 ( $*/\div$  1.07); Table 1), thus demonstrating the validity of the DXA method. Previously,  
252 the digitizing process for calculating  $d_{PT}$  from 2D X-ray video fluoroscopy has been  
253 reported as having a very high reliability (CV of 1.23%) (Baltzopoulos, 1995) but to our  
254 knowledge, test-retest reproducibility of the entire  $d_{PT}$  assessment from X-ray images  
255 (including multiple scans of the same knees) has not been reported. This could be due to  
256 the high radiation emitted during a standard radiograph compared to the low effective  
257 dose during an IVA DXA scan (Damilakis et al., 2010). Therefore, not only does this  
258 study demonstrate the high reproducibility of the entire 2D assessment of  $d_{PT}$  via DXA  
259 at rest, but it reflects the high reliability of identifying the correct anatomical landmarks,  
260 i.e. the medial and lateral tibiofemoral contact points, patella apex and the tibial  
261 tuberosity, on multiple occasions from a single X-ray image (Baltzopoulos, 1995; Chow  
262 et al., 2006; Kellis and Baltzopoulos, 1999). Using 2D MRI scans to identify the  
263 geometric centre of the femoral condyles (GCFC) as the reference point for the centre

264 of rotation, other investigators have reported the typical error, which provides an  
265 indication of the test-retest reliability, as 0.5 mm (O'Brien et al., 2009). This value was  
266 comparable to the 0.9 mm and 1.0 mm for our MRI and DXA methods, respectively  
267 (data not reported). Thus, the reliability of our novel DXA method for determining  $d_{PT}$   
268 was comparable not only to the TFCP MRI method reported in our study, but also to a  
269 different method incorporating 2D MR images and the GCFC reference point for the  
270 centre of knee joint rotation (O'Brien et al., 2009).

271

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

287

288 **Conclusion**

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

295

296 **Conflict of interest**

The authors declare no conflict of interest.

**REFERENCES**

- 297 Baltzopoulos, V., 1995. A videofluoroscopy method for optical distortion correction  
298 and measurement of knee-joint kinematics. *Clin Biomech (Bristol, Avon)* 10, 85-92.
- 299 Burk, A., Timpmann, S., Medijainen, L., Vahi, M., Oopik, V., 2009. Time-divided  
300 ingestion pattern of casein-based protein supplement stimulates an increase in fat-free  
301 body mass during resistance training in young untrained men. *Nutr Res* 29, 405-413.
- 302 Burke, D.G., Chilibeck, P.D., Davidson, K.S., Candow, D.G., Farthing, J., Smith-  
303 Palmer, T., 2001. The effect of whey protein supplementation with and without creatine  
304 monohydrate combined with resistance training on lean tissue mass and muscle  
305 strength. *Int J Sport Nutr Exerc Metab* 11, 349-364.
- 306 Chow, J.W., Park, S.A., Wight, J.T., Tillman, M.D., 2006. Reliability of a technique for  
307 determining sagittal knee geometry from lateral knee radiographs. *The Knee* 13, 318-  
308 323.
- 309 Cummings, S.R., Cauley, J.A., Palermo, L., Ross, P.D., Wasnich, R.D., Black, D.,  
310 Faulkner, K.G., 1994. Racial differences in hip axis lengths might explain racial  
311 differences in rates of hip fracture. Study of Osteoporotic Fractures Research Group.  
312 *Osteoporos Int* 4, 226-229.
- 313 Damilakis, J., Adams, J.E., Guglielmi, G., Link, T.M., 2010. Radiation exposure in X-  
314 ray-based imaging techniques used in osteoporosis. *European radiology* 20, 2707-2714.
- 315 Duan, Y., Turner, C.H., Kim, B.T., Seeman, E., 2001. Sexual dimorphism in vertebral  
316 fragility is more the result of gender differences in age-related bone gain than bone loss.  
317 *J Bone Miner Res* 16, 2267-2275.
- 318 Erskine, R.M., Jones, D.A., Maganaris, C.N., Degens, H., 2009. In vivo specific tension  
319 of the human quadriceps femoris muscle. *Eur J Appl Physiol* 106, 827-838.
- 320 Erskine, R.M., Jones, D.A., Williams, A.G., Stewart, C.E., Degens, H., 2010.  
321 Resistance training increases in vivo quadriceps femoris muscle specific tension in  
322 young men. *Acta Physiol (Oxf)* 199, 83-89.
- 323 Faulkner, K.G., Cummings, S.R., Black, D., Palermo, L., Gluer, C.C., Genant, H.K.,  
324 1993. Simple measurement of femoral geometry predicts hip fracture: the study of  
325 osteoporotic fractures. *J Bone Miner Res* 8, 1211-1217.
- 326 Faulkner, K.G., Cummings, S.R., Nevitt, M.C., Pressman, A., Jergas, M., Genant, H.K.,  
327 1995. Hip axis length and osteoporotic fractures. Study of Osteoporotic Fractures  
328 Research Group. *J Bone Miner Res* 10, 506-508.
- 329 Hartman, J.W., Tang, J.E., Wilkinson, S.B., Tarnopolsky, M.A., Lawrence, R.L.,  
330 Fullerton, A.V., Phillips, S.M., 2007. Consumption of fat-free fluid milk after resistance  
331 exercise promotes greater lean mass accretion than does consumption of soy or  
332 carbohydrate in young, novice, male weightlifters. *Am J Clin Nutr* 86, 373-381.



- 333 Hashizume, S., Iwanuma, S., Akagi, R., Kanehisa, H., Kawakami, Y., Yanai, T., 2012.  
334 In vivo determination of the Achilles tendon moment arm in three-dimensions. *J*  
335 *Biomech* 45, 409-413.
- 336 Imran, A., Huss, R.A., Holstein, H., O'Connor, J.J., 2000. The variation in the  
337 orientations and moment arms of the knee extensor and flexor muscle tendons with  
338 increasing muscle force: a mathematical analysis. *Proceedings of the Institution of*  
339 *Mechanical Engineers. Part H, Journal of engineering in medicine* 214, 277-286.
- 340 Josse, A.R., Tang, J.E., Tarnopolsky, M.A., Phillips, S.M., 2010. Body composition and  
341 strength changes in women with milk and resistance exercise. *Med Sci Sports Exerc* 42,  
342 1122-1130.
- 343 Kamimura, M.A., Avesani, C.M., Cendoroglo, M., Canziani, M.E., Draibe, S.A.,  
344 Cuppari, L., 2003a. Comparison of skinfold thicknesses and bioelectrical impedance  
345 analysis with dual-energy X-ray absorptiometry for the assessment of body fat in  
346 patients on long-term haemodialysis therapy. *Nephrol Dial Transplant* 18, 101-105.
- 347 Kamimura, M.A., Jose Dos Santos, N.S., Avesani, C.M., Fernandes Canziani, M.E.,  
348 Draibe, S.A., Cuppari, L., 2003b. Comparison of three methods for the determination of  
349 body fat in patients on long-term hemodialysis therapy. *J Am Diet Assoc* 103, 195-199.
- 350 Kellis, E., Baltzopoulos, V., 1999. In vivo determination of the patella tendon and  
351 hamstrings moment arms in adult males using videofluoroscopy during submaximal  
352 knee extension and flexion. *Clin Biomech (Bristol, Avon)* 14, 118-124.
- 353 Kerksick, C.M., Rasmussen, C.J., Lancaster, S.L., Magu, B., Smith, P., Melton, C.,  
354 Greenwood, M., Almada, A.L., Earnest, C.P., Kreider, R.B., 2006. The effects of  
355 protein and amino acid supplementation on performance and training adaptations during  
356 ten weeks of resistance training. *J Strength Cond Res* 20, 643-653.
- 357 Kohrt, W.M., 1998. Preliminary evidence that DEXA provides an accurate assessment  
358 of body composition. *J Appl Physiol* 84, 372-377.
- 359 Macaluso, A., Nimmo, M.A., Foster, J.E., Cockburn, M., McMillan, N.C., De Vito, G.,  
360 2002. Contractile muscle volume and agonist-antagonist coactivation account for  
361 differences in torque between young and older women. *Muscle Nerve* 25, 858-863.
- 362 Nevill, A.M., Atkinson, G., 1997. Assessing agreement between measurements  
363 recorded on a ratio scale in sports medicine and sports science. *Br J Sports Med* 31,  
364 314-318.
- 365 O'Brien, T.D., Reeves, N.D., Baltzopoulos, V., Jones, D.A., Maganaris, C.N., 2009.  
366 Moment arms of the knee extensor mechanism in children and adults. *J Anat* 215, 198-  
367 205.
- 368 Onambele-Pearson, G.L., Pearson, S.J., 2012. The magnitude and character of  
369 resistance-training-induced increase in tendon stiffness at old age is gender specific.  
370 *Age (Dordrecht, Netherlands)* 34, 427-438.

- 371 Prior, B.M., Cureton, K.J., Modlesky, C.M., Evans, E.M., Sloniger, M.A., Saunders,  
372 M., Lewis, R.D., 1997. In vivo validation of whole body composition estimates from  
373 dual-energy X-ray absorptiometry. *J Appl Physiol* 83, 623-630.
- 374 Reeves, N.D., Narici, M.V., Maganaris, C.N., 2004a. Effect of resistance training on  
375 skeletal muscle-specific force in elderly humans. *J Appl Physiol* 96, 885-892.
- 376 Reeves, N.D., Narici, M.V., Maganaris, C.N., 2004b. In vivo human muscle structure  
377 and function: adaptations to resistance training in old age. *Exp Physiol* 89, 675-689.
- 378 Tsaopoulos, D.E., Baltzopoulos, V., Richards, P.J., Maganaris, C.N., 2007a. In vivo  
379 changes in the human patellar tendon moment arm length with different modes and  
380 intensities of muscle contraction. *J Biomech* 40, 3325-3332.
- 381 Tsaopoulos, D.E., Baltzopoulos, V., Richards, P.J., Maganaris, C.N., 2009. A  
382 comparison of different two-dimensional approaches for the determination of the  
383 patellar tendon moment arm length. *Eur J Appl Physiol* 105, 809-814.
- 384 Tsaopoulos, D.E., Maganaris, C.N., Baltzopoulos, V., 2007b. Can the patellar tendon  
385 moment arm be predicted from anthropometric measurements? *J Biomech* 40, 645-651.
- 386 Westphal, C.J., Schmitz, A., Reeder, S.B., Thelen, D.G., 2013. Load-dependent  
387 variations in knee kinematics measured with dynamic MRI. *J Biomech* 46, 2045-2052.
- 388 Wilson, N.A., Sheehan, F.T., 2009. Dynamic in vivo 3-dimensional moment arms of the  
389 individual quadriceps components. *J Biomech* 42, 1891-1897.
- 390 Wretenberg, P., Nemeth, G., Lamontagne, M., Lundin, B., 1996. Passive knee muscle  
391 moment arms measured in vivo with MRI. *Clin Biomech (Bristol, Avon)* 11, 439-446.  
392

**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  $\pm$  SD.

	<b>DXA</b>	<b>MRI</b>
$d_{PT}$ (mm)	42.70 $\pm$ 3.93	38.91 $\pm$ 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 (*/ $\div$ 1.07)	1.00 (*/ $\div$ 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;  $n = 12$ .