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1 **Achilles tendon moment arm length is smaller in children with cerebral palsy than in**
2 **typically developing children**

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23 **Abstract**

24 When studying muscle and whole-body function in children with cerebral palsy (CP),
25 knowledge about both internal and external moment arms is essential since they determine
26 the mechanical advantage of a muscle over an external force. Here we asked if Achilles
27 tendon moment arm (MA_{AT}) length is different in children with CP and age-matched
28 typically developing (TD) children, and if MA_{AT} can be predicted from anthropometric
29 measurements. Sixteen children with CP (age: 10y 7m \pm 3y, 7 hemiplegia, 12 diplegia,
30 GMFCS level: I (11) and II (8)) and twenty TD children (age: 10y 6mo \pm 3y) participated in
31 this case-control study. MA_{AT} was calculated at 20° plantarflexion by differentiating
32 calcaneus displacement with respect to ankle angle. Seven anthropometric variables were
33 measured and related to MA_{AT} . We found normalized MA_{AT} to be 15% (~7mm) smaller in
34 children with CP compared to TD children ($p=0.003$). MA_{AT} could be predicted by all
35 anthropometric measurements with tibia length explaining 79% and 72% of variance in
36 children with CP and TD children, respectively. Our findings have important implications for
37 clinical decision making since MA_{AT} influences the mechanical advantage about the ankle,
38 which contributes to movement function and is manipulated surgically.

39

40 **Introduction**

41 The mechanical advantage of a joint determines the internal muscle force needed to overcome
42 an external resistance, e.g. ground reaction force. Mechanical advantage is defined as the ratio
43 of internal to external moment arm (MA) length, and has been shown to influence joint and
44 whole body function (Lee and Piazza, 2009). Differences in either MA can alter the outcome
45 of muscle contraction, even if muscle function remains unaltered. In situations where
46 movement function may be impaired and the study of muscle function is important, such as
47 cerebral palsy (CP) (Barber et al., 2011), knowledge of MA length and mechanical advantage
48 is vital if we are to understand the nature of impairment and how best to intervene.

49 Cerebral palsy commonly presents with bony deformities due to increased muscle forces acting
50 on the bone (Morrell et al., 2002), which can cause ‘lever-arm dysfunction’ (Novacheck and
51 Gage, 2007). At the ankle, an altered external lever-arm may be related to equinus, a midfoot
52 break or tibial torsion, all of which shorten the external MA. Surgical interventions are
53 recommended to increase external MA length (Gage et al., 2009). In the case of equinus,
54 surgical lengthening of the Achilles tendon can improve kinematics, but weakness of the
55 plantar flexors can occur as an adverse outcome of surgery (Gage, 2004). To understand the
56 effects of surgical interventions that alter external MA, we need to consider how they will
57 change the mechanical advantage. However, the length of the Achilles tendon moment arm
58 (MA_{AT}), its contribution to mechanical advantage, and the influence it has on surgical outcomes
59 is often not considered in clinical decision making.

60 The internal MA about which a muscle operates also determines more fundamental measures
61 of joint function (Lieber and Friden, 2000). MA is proportional to maximum joint moment,
62 typically referred to as muscle strength and the excursion range over which a muscle acts. Thus,
63 differences in MA will affect the force-length properties of the muscle. Moreover, an altered

64 muscle excursion over a similar range of motion (ROM) would also necessitate a different
65 muscle shortening velocity, which influences the force-velocity characteristics (Lieber, 2002).
66 Furthermore, MA length is an important feature that determines the outcomes of
67 musculoskeletal modelling. When using these models in children, typically developing (TD)
68 or with CP, MA lengths are typically scaled down from adults using a 1:1 proportionality across
69 all structures and dimensions (Sloot et al., 2015), but it is not clear if this is a valid way to scale
70 (O'Brien et al., 2009; Waugh et al., 2011). Inappropriate scaling can lead to erroneous
71 conclusions concerning muscle length and produced forces (Scheys et al., 2008).

72 In children with CP, the plantarflexor muscles are often affected by spasticity and contracture,
73 and the foot and ankle joint by deformities. Currently, the focus lies on how these deformities
74 affect the external MA, but we do not know how MA_{AT} may be altered. A previous study
75 reported smaller muscle excursion over a common ROM in CP vs. TD children, which the
76 authors hypothesised may be related to shorter MA_{AT} in the CP group (Matthiasdottir et al.,
77 2014). However, since excursion was measured at the myotendinous junction (MTJ) and
78 possible alterations in Achilles tendon lengthening during ankle joint rotation are unknown,
79 the smaller muscle excursion may be caused by either a shorter MA_{AT} or greater Achilles
80 tendon deformation. So far, no studies have directly measured MA_{AT} lengths in children with
81 CP. Therefore, the purpose of this study was to quantify MA_{AT} length in children with CP and
82 TD children using the tendon excursion (TE) method with tendon displacement measured at its
83 distal attachment to the calcaneus. Also we wanted to establish if MA_{AT} in both groups can be
84 predicted from anthropometric measurements. We hypothesized that MA_{AT} is smaller in
85 children with CP compared with TD children, and that in both groups MA_{AT} is predictable from
86 anthropometry.

87 **Method**

88 *Participants:*

89 Thirty-six children aged 6-16 years were recruited for this study. Sixteen children were
90 diagnosed with spastic CP and twenty age-matched TD children served as a control group.
91 Exclusion criteria were having botulinum toxin injection to the lower limb muscles within six
92 months prior to testing or any lower limb orthopaedic surgery. All TD children were free from
93 neuromuscular or skeletal disorders. Children were recruited through the gait lab of Alder Hey
94 Children's Hospital in Liverpool and the University Hospital in Leuven. The study was
95 approved by the Institutional as well as the NHS research ethics committee in the UK and the
96 University Hospital's ethics committee in Leuven. The study was conducted in accordance
97 with the Declaration of Helsinki. Written parental consent was obtained from the parents, and
98 written assent was given by children in accordance with local regulations.

99 *Procedure:*

100 Participants lay prone on a bed with their leg in a custom made orthosis, to lock knee angle at
101 20° flexion and control ankle movement to occur only in the sagittal plane (Figure 1A). The
102 axis of rotation of the orthosis was aligned with the lateral malleolus. The leg tested was the
103 most affected, defined by spasticity scores, in the CP group and the left in the TD group. During
104 each trial, the foot was passively rotated by an experimenter from maximum plantarflexion
105 (PF) to maximum dorsiflexion (DF), taking five seconds to complete the ROM while ankle
106 angle, calcaneus displacement, muscle activity and joint moment were measured.

107 This procedure was repeated six times with a minimum of 10 s of rest between each repetition.
108 Participants were instructed to relax their muscles during the movements, which was checked
109 for post-processing by inspection of surface electromyography (sEMG) of the Triceps Surae
110 muscles at 1600 Hz (Zerowire, Cometa, Milan, IT). Forces and moments applied at the ankle
111 were measured using a six degrees of freedom force sensor load-cell (ATI mini45: Industrial

112 Automation) attached to the orthosis under the ball of the foot. Ankle angle and calcaneus
113 displacement along the length of the shank were calculated from the 3D position of two clusters
114 of markers placed on the foot-plate of the orthosis and the shank and a single marker on the
115 most superficial part of the posterior calcaneal tuberosity (Optitrack, US). Kinematic data was
116 sampled at 120 HZ and kinetic data at 200 Hz.

117 *Data processing:*

118 Data analysis was carried out using custom made software (Matlab R2015a, Python 2.7.11).
119 Kinematic and kinetic data were filtered using a 2nd order low pass Butterworth filter with a
120 cut-off frequency of 6 Hz. Net ankle joint moment was calculated according to equation 1:

121
$$M_{joint} = -F_z d_z - F_y d_y - M_x - M_{orth}$$

122 Where F_z , F_y and M_x are the forces and moment exerted on the load cell in the z, y and x
123 direction respectively, d_z and d_y are the moment arm distances from the point of force
124 application of the load-cell to the lateral malleolus (see free body diagram, figure 1B) and M_{orth}
125 is the predicted moment caused by gravity on the orthotic (Bar-On et al., 2013; Schless et al.,
126 2015).

127 *Calculation of MA_{AT}:*

128 MA_{AT} was determined using the tendon excursion (TE) method (An et al., 1984; Ito et al.,
129 2000), which defines MA as the ratio between linear displacement of the tendon and the change
130 in joint angle ($MA_{AT} = \frac{\delta_{calc}}{\theta}$). Here, linear displacement of the Achilles tendon was defined at
131 its insertion on the calcaneus, and measured from the displacement of a marker on the calcaneus
132 along the direction of the tibia (δ_{calc}), corrected for marker size and skin thickness. A separate
133 pilot experiment has shown that the marker on the skin was a valid representation of the distal
134 insertion of the Achilles tendon (Supplementary material).

135 For each participant, calcaneus displacement vs. ankle angle curves were constructed for six
136 passive dorsiflexion movements. In some children, a mid-foot break or heel lift out of the
137 orthosis was apparent towards maximum dorsiflexion, identifiable by plateauing of the
138 displacement-angle curve. In these cases, curves were trimmed to a smaller ROM. The
139 calculated joint moments were checked over this trimmed ROM. At angles common to most
140 participants, passive joint moments were typically ~1 Nm (Table 1) and were considered to be
141 sufficiently low to not violate the assumptions of the TE method and allow us to continue the
142 calculation of MA_{AT} at all angles (Olszewski et al., 2015). Next, a second order polynomial
143 was fitted through the six trimmed displacement-angle relationships ($0.97 < r^2 < 0.99$). A second
144 order polynomial allowed for the possibility for MA_{AT} to change with ankle angle. These
145 polynomials were differentiated to construct a MA_{AT} -ankle angle relationship for each
146 participant. These individual MA_{AT} -angle graphs within the trimmed ROM are plotted in
147 Figure 2A. As the ROM over which MA_{AT} could be calculated was different for each
148 participant, we selected MA_{AT} at one common ankle angle that most participants could achieve
149 (-20° , with negative angles expressing plantarflexed position) for further calculations. Valid
150 comparison of MA_{AT} at a single angle relies on equal slopes of the MA_{AT} -angle relationship
151 between subjects. To test this assumption, the average gradients of the MA_{AT} -angle relations
152 were compared between groups. In the CP group, one participant was excluded because the
153 gradient of the MA_{AT} -angle relationship was determined as an outlier, i.e. exceeding ' $Q3 \pm 1.5$
154 $\cdot (Q3 - Q1)$ ', with $Q1$ and $Q3$ being the 25th and 75th percentiles. Furthermore, this profile was
155 judged to be physiologically implausible (4cm change over a couple degrees). After removing
156 the outlier, within groups, all gradients were within 2.7 SD from the mean and considered
157 similar within and between groups ($p=0.27$, 95% CI [-0.1, 0.37]) (Figure 2B). These lengths
158 were then corrected for marker size (11 mm diameter) by subtracting 5.5 mm. Finally, the

159 individual distance measured from the surface of the skin to the attachment of the Achilles
160 tendon on the calcaneus was measured with B-mode ultrasound and subtracted from the MA_{AT}.

161

162 *Anthropometric measurements:*

163 Seven anthropometric variables (Table 2) were measured by a trained physiotherapist: height,
164 body mass, leg length (LL), tibia length (TL), foot length (FL), distance between medial and
165 lateral malleolus (MD) and age. These parameters were assessed for predictive power and
166 normalization of MA_{AT}. Tibial torsion was measured while the participant was lying prone
167 with the knee in 90° flexion as the angle between the line of the longitudinal axis of the thigh
168 and a line perpendicular to the axis connecting the most prominent points of the medial and
169 lateral malleolus.

170 *Statistics:*

171 All parameters were checked to be normally distributed using the Shapiro-Wilk test and by
172 inspection of the q-q plots. To determine if MA_{AT} could be predicted from anthropometric
173 measurements, a backwards stepwise multiple regression analysis was performed as well as
174 linear regressions between MA_{AT} and each anthropometric measurement separately, of which
175 Pearson r^2 -values were calculated. Based on the r^2 -values of significant relationships it was
176 decided whether, and to which, anthropometric dimension MA_{AT} could be normalized.
177 Absolute and normalized MA_{AT} were then compared between groups with a 2-sample
178 independent t-test. The level of statistical significance was set at $p \leq 0.05$.

179 **Results**

180 Data of fifteen children with CP and twenty TD children was used for the final MA_{AT}
181 calculations. No differences were found between the groups for any of the anthropometric
182 measurements. Participant characteristics can be found in Table 3. In the current sample of

183 children with CP, TT was between $0^\circ < \alpha < 20^\circ$ (Median: 15° , IQR: $10-20^\circ$), which is similar to
184 the tibial torsion range considered as “typical” (Mudge et al., 2014).

185 Correlations between MA_{AT} at -20° and each anthropometric measure showed mostly strong
186 positive relationships ($p < 0.01$, $r^2 = 0.36-0.81$, figure 3). Based on the high combined
187 correlation across both groups, it was decided most appropriate to scale MA_{AT} to TL.

188 When MA_{AT} was normalized to TL, children with CP had significantly smaller MA_{AT} than TD
189 children ($p = 0.001$, 95% CI [1.05, 3.96]). This difference was consistent over the ROM studied
190 (-30° to -5°) and its magnitude ranged from 1.4 to 2.5 %TL across the ROM. Absolute MA_{AT}
191 were not significantly different between groups ($p = 0.0544$, 95% CI [-0.15, 14.91]).

192 Linear regressions were performed with all anthropometric variables as separate predictors
193 (Table 4). MA_{AT} could be significantly predicted by all variables independently in both
194 children with CP and TD children. Inclusion of more variables in the regression did not
195 improve predictive power (single regressions' $r^2 \sim 0.7$, vs. multiple regression $r^2 \sim 0.65$).

196 **Discussion**

197 The aim of this study was to quantify MA_{AT} in children with CP and TD children, and to
198 determine whether this can be predicted from anthropometrics. We found that MA_{AT} in
199 children with CP is 15% ($\sim 7\text{mm}$) smaller than in TD children throughout an ankle ROM of -
200 30° to -5° . Also, it was shown that in both groups MA_{AT} scales with, and can be predicted using
201 a range of anthropometric measurements.

202 The relationship between internal and external MA around the joint reflects the mechanical
203 advantage. This is an important feature when trying to explain ankle joint function in
204 pathological gait. Considering a simplified scenario when a child is standing stationary on the
205 forefoot, the smaller MA_{AT} in children with CP, would be associated with a smaller mechanical
206 advantage at the ankle if it was not for the external MA also being smaller, for example due to

207 equinus or other external MA deformities. The combination may actually mean that mechanical
208 advantage does not turn out to be very different to typical (Figure 4A&B). Orthopaedic
209 treatment, typically aiming to correct external MA length by optimizing foot shape and foot
210 progression angle, will increase the external MA and thereby reduce the mechanical advantage.
211 This would happen regardless of MA_{AT} length, but our results indicate that the mechanical
212 advantage would not be restored to typical as intended, but in fact be reduced to less than
213 typical (Figure 4C). This could be one of the contributing factors to the observed weakness of
214 the plantar flexor muscles after equinus correcting surgery (Gage, 2004; Orendurff et al., 2002).
215 Further research should focus on the specific influence of orthopaedic surgeries correcting
216 lever arm dysfunction on the mechanical advantage of the ankle. Also, studies should seek to
217 determine MA_{AT} length during gait, and under loading conditions (Rasske et al., 2016).

218 A smaller MA_{AT} also brings about changes in the moment-angle relationship. Shorter MA_{AT}
219 would generate smaller maximal joint moments even when the same maximal muscle force is
220 generated. Also, with a shorter MA_{AT} , the same muscle excursion will cause a larger joint
221 rotation. Consequently, a joint moment can be produced over a broader ROM (Figure 5A). As
222 less muscle excursion during joint rotation corresponds to lower angular velocities, joint
223 moment would decline less as joint velocity increases (Figure 5B). Consequently, the shorter
224 MA_{AT} of children with CP has the effect of creating joint function similar to that associated
225 with a muscle with long fascicles and small physiological cross-sectional area (Lieber and
226 Friden, 2000).

227 Spasticity is a major problem in children with CP, generally defined as a ‘velocity-dependent
228 increase in muscle activity’ (Lance, 1980). Assessments of spasticity rotate the joint at high
229 velocities to elicit a response (Bar-On et al., 2013). Since a shorter MA leads to a smaller
230 muscle lengthening velocity when rotating the joint, relating angular velocities to muscle
231 stretch will likely underestimate the true sensitivity of the muscle (Bar-On et al., 2014).

232 The smaller MA_{AT} in children with CP might be due to alterations in bony architecture or the
233 development of bony deformities. Muscle thickness could also play a role (Maganaris et al.,
234 1998), since this would influence the trajectory of the tendon's action line and so its distance
235 from the centre of joint rotation. Children with CP have a smaller muscle cross sectional area
236 than TD children (Barber et al., 2011), so this could contribute to the smaller MA_{AT} . Future
237 studies should aim to confirm the exact cause of the decreased MA_{AT} in children with CP.

238 When using musculoskeletal models to study movement function, MAs are central in
239 calculating muscle forces and lengths. Here we confirm that conventional scaling using a 1:1
240 proportionality across all structures and dimensions is not valid for scaling between adults and
241 children. In addition, we show that applying any scaling algorithm similarly in children with
242 CP and TD children is invalid. Therefore, we provide predictive equations to calculate MA_{AT}
243 at -20° in children aged 6-16 years. We found the profile of the MA-angle relationship to be
244 not significantly different within and between groups, this means that a) comparing MA_{AT} at a
245 single joint angle is valid for the ROM described, and b) we can combine the predicted MA_{AT}
246 with the known gradient (-0.9 vs -1.03 mm/deg, for CP and TD respectively) to calculate MA_{AT}
247 at angles between -30° to -5° . More research is needed to extend these relationships over a full
248 ROM.

249 Similar results concerning the predictability of patellar tendon MA have been shown in TD
250 children (O'Brien et al., 2009), where tibia length was shown to be one of the main predictors.
251 On the other hand, Waugh et al. (2011) concluded that due to low r^2 -values, MA_{AT} could not
252 be predicted from anthropometrics in TD children aged 5-12 years. The contrast with the
253 present findings may be explained by the larger age range used in this study and thus an
254 increased power to detect correlations.

255 This study has a few limitations. The sample size is relatively small for a heterogeneous
256 population like children with CP. However, the statistical power of our comparison of MA_{AT}
257 length between groups was 0.88, which suggests the sample was adequate for our purpose
258 (Chow et al., 2003). Different methods can be used to calculate MA_{AT} length, and each has
259 some limitations. In this study we used the TE method to define MA_{AT}, which has been shown
260 to correlate well with MRI based methods (Fath et al., 2010). To exclude deformation of the
261 tendon as a possible source of error we measured tendon displacement at the distal end of the
262 tendon instead of proximally at the MTJ (Maganaris et al., 2000). Even with this step, the TE
263 method used relies on several assumptions. First, it is assumed that the tensile load applied to
264 the muscle-tendon was constantly low and thus it does not cause any deformations (Olszewski
265 et al., 2015). We confirmed passive net joint moments to be low (~0-1 Nm) across the ROM
266 studied, therefore we believe that no confounding tissue deformations have been introduced.
267 Second, the TE method assumes ankle rotation to occur within the sagittal plane (Maganaris,
268 2004). However, the tibio-talar joint axis is typically externally rotated by an angle of $15\pm 5^\circ$,
269 which leads to an overestimation of MA_{AT}. In children with CP, tibial torsion can cause this
270 angle to deviate from typical values. In the current study, tibial torsion, as measured by the
271 bimalleolar angle, was within typical range, reducing the likelihood that it would have
272 confounded our comparisons (Mudge et al., 2014). Unfortunately, this method of assessing
273 tibial torsion has low correlation to more accurate radiological measures (Lee et al., 2009). To
274 individually correct MA_{AT} for tibial torsion, better imaging techniques are necessary.

275 To conclude, this study has shown for the first time that Achilles tendon moment arm (MA_{AT})
276 is smaller in children with CP compared to TD children. This has important implications in
277 clinical decision making since MA_{AT} influences the mechanical advantage about the ankle,
278 which contributes to movement function and is manipulated surgically. We also found that
279 both in TD children and in children with CP, MA_{AT} can be predicted from anthropometric

280 measurements, which allows realistic quantification for relevant modelling applications
281 without access to medical imaging facilities.

282 **Conflict of interest**

283 The authors disclose that they have no conflicts of interest.

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288 engineering, KU Leuven, for his help with the calculations of net joint torque.

289

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366

367 **Table 1:** minimal, maximal and average joint moments measured at each ankle angle in the common
 368 ROM in typically developing (TD) and cerebral palsy (CP) participants.

	-30°		-25°		-20°		-15°		-10°		-5°	
	TD	CP										
Min (Nm)	-1.3	-0.9	-1.4	-0.9	-1.2	-0.8	-0.9	-0.6	-0.7	-0.4	-0.5	-0.2
Max (Nm)	-0.7	-0.1	-0.6	-0.1	-0.3	0.2	0.2	1.0	1.0	2.4	2.3	4.9
Mean (Nm)	-0.9	-0.7	-0.9	-0.6	-0.7	-0.4	-0.3	0.1	0.1	0.8	0.7	2.3

369

370 **Table 2:** definitions of anthropometric variables

Measure	Method
Tibia length	Distance from the tibiofemoral joint space to lateral malleolus
Leg length	Distance from the anterior superior iliac spine to the medial malleolus
Foot length	Distance from lateral malleolus to the head of metatarsal two
Inter-malleolar distance	Distance from the medial to lateral malleolus measured with 3d motion capture.

371

372 **Table 3:** Participant characteristics

Participant characteristics	CP (n=15)	TD (n=20)
Age (years)	11.1 (3.05)	10.4 (3.4)
Male/female (n)	10/5	11/9
Height (cm)	140.5 (20.6)	141.5 (16.6)
Mass (kg)	34.6 (18)	37 (14)
GMFCS (I-IV) (n)	10 I, 5 II	n/a
Diagnosis (n)	9 Diplegia, 6 Hemiplegia	n/a
Modified Ashworth Score (n=7) and Average Modified Tardieu (n=7) *	MAS: 1 (n=1), 1.5 (n=6), 3 (n=1) Tardieu: 2 (n=5), 3 (n=2)	n/a

Data are mean (SD) unless otherwise stated. CP: cerebral palsy; TD: typically developing; GMFCS: gross motor functional classification scale; n/a: not applicable.

*Tardieu scores from children recruited at Alder Hey Children's Hospital in Liverpool. MAS from children recruited at University Hospital in Leuven. One participant unknown.

373

374 **Table 4:** predictive equations to calculate MA_{AT} at -20° , r^2 and p values for all anthropometric
 375 variables are shown. TL: tibia length, LL: leg length, FL: foot length, MD: distance between medial
 376 and lateral malleoli.

	Formula	r²	p
CP			
TL (mm)	$MA_{CP} = -26.1 + 0.20 * TL$	0.79	<0.01
Height (cm)	$MA_{CP} = -38.7 + 0.57 * Height$	0.80	<0.01
Body mass (kg)	$MA_{CP} = 20.4 + 0.60 * Body\ mass$	0.66	<0.01
LL (cm)	$MA_{CP} = -26.2 + 0.93 * LL$	0.81	<0.01
FL (cm)	$MA_{CP} = -57.3 + 7.23 * FL$	0.79	<0.01
MD (mm)	$MA_{CP} = -27.9 + 1.13 * MD$	0.67	<0.01
Age (y)	$MA_{CP} = 2.45 + 3.52 * age$	0.70	<0.01
TD			
TL (mm)	$MA_{TD} = -8.2 + 0.17 * TL$	0.72	<0.01
Height (cm)	$MA_{TD} = -13.1 + 0.44 * Height$	0.65	<0.01
Body mass (kg)	$MA_{TD} = 28.9 + 0.53 * Body\ mass$	0.68	<0.01
LL (cm)	$MA_{TD} = -7.8 + 0.78 * LL$	0.71	<0.01
FL (cm)	$MA_{TD} = -22.1 + 5.00 * FL$	0.57	<0.01
MD (mm)	$MA_{TD} = -7.2 + 0.90 * MD$	0.36	<0.01
Age (y)	$MA_{TD} = 27.1 + 2.04 * age$	0.55	<0.01

377

378

379 **Figure Legends**

380 **Figure 1: A)** Experimental setup of the ankle in the orthosis. Two clusters of markers were
381 used to calculate ankle angle and a marker on the calcaneus was used to calculate calcaneus
382 displacement. The load cell was used to calculate joint moments. During the experiment the
383 ankle was moved from plantar to dorsiflexion. **B)** Free body diagram of the foot and foot plate.
384 d_y and d_z correspond to the moment arm distances from the point of force application,
385 respectively F_y and F_z , of the load-cell to the lateral malleolus. M_x is the moment exerted on
386 the load cell in the x direction. $M_{orthosis}$ is the calculated moment caused only by the weight of
387 the orthosis. The joint moment is given by: $M_{joint} = -F_z d_z - F_y d_y - M_x - M_{orthosis}$

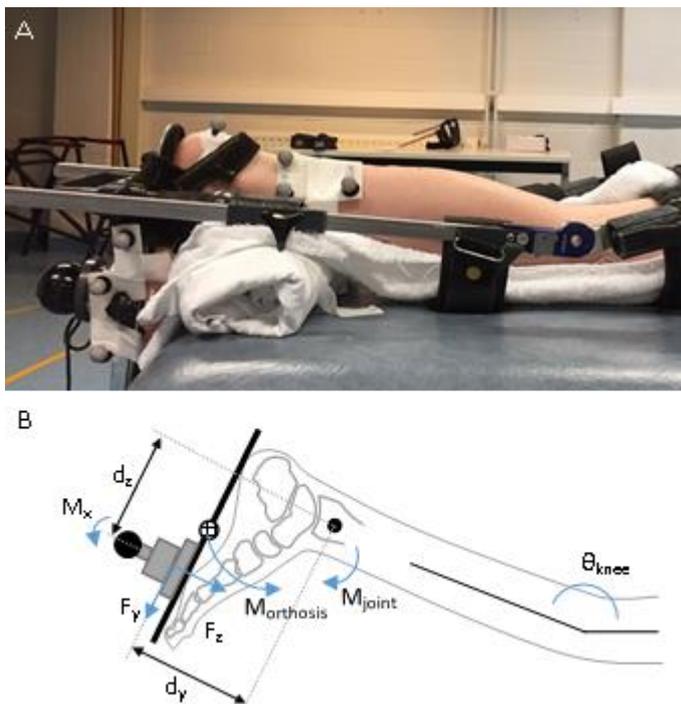
388 **Figure 2: A:** Absolute Achilles tendon moment arm (MA_{AT}) length vs ankle angle for typically
389 developing children (TD) and children with cerebral palsy (CP). Six angles common to most
390 participants at 5° intervals between -30° and -5° were identified where we could record
391 calcaneus excursion accurately. The boxes above each joint angle indicate the number of
392 children in each group for which MA_{AT} could be calculated at that specific angle. -20° was the
393 angle achieved by the most children. **B:** Box and whisker plot of gradient of the MA_{AT} vs angle
394 curves in TD children and children with CP. * represents one outlier that was removed from
395 further analysis. The edges of the box correspond to the 25th and 75th percentiles. The whiskers
396 correspond to 2.7σ and cover 99.3 percent of all data.

397 **Figure 3:** Correlations between anthropometric variables and Achilles tendon moment arms
398 (MA_{AT}) in children with cerebral palsy (CP) and typically developing children (TD). TL: tibia
399 length, LL: leg length, FL: foot length and MD: inter malleolar distance.

400 **Figure 4:** Schematic drawing of the foot with the ground reaction force (GRF) and muscle
401 force (F_m) acting over the external moment arm (MA_{ext}) and Achilles tendon moment arm
402 (MA_{AT}) respectively. a: TD child, b: a child with CP in equinus and c: a child with CP where

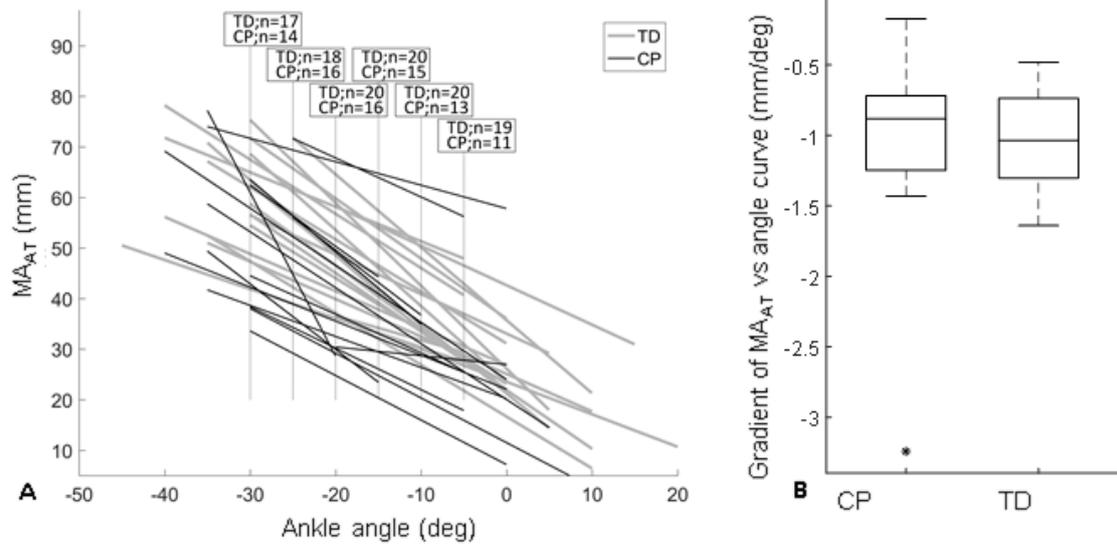
403 surgery has lengthened the MA_{ext} but not altered the MA_{AT} . For simplicity, GRF and F_m are
404 shown to act at right angles to the horizontal. In a and b, the ratio between MA_{AT} and MA_{ext}
405 reflects the mechanical advantage and will be close to typical in the child with CP. c: When the
406 MA_{ext} is lengthened the mechanical advantage will be decreased.

407 **Figure 5:** Schematic moment-angle (a) and moment-angular velocity (b) relationships of two
408 identical muscles with different moment arm lengths. Muscles of children with cerebral palsy
409 (CP) have smaller moment arms than typically developing (TD) children, all other muscle
410 properties are considered to be identical. TD muscle will produce a larger peak moment for a
411 given muscle force, however the active range of force production is larger in CP joint.
412 Similarly, peak joint moment is larger in TD muscles, however, with increasing velocity the
413 decline in joint moment is less in CP muscles.

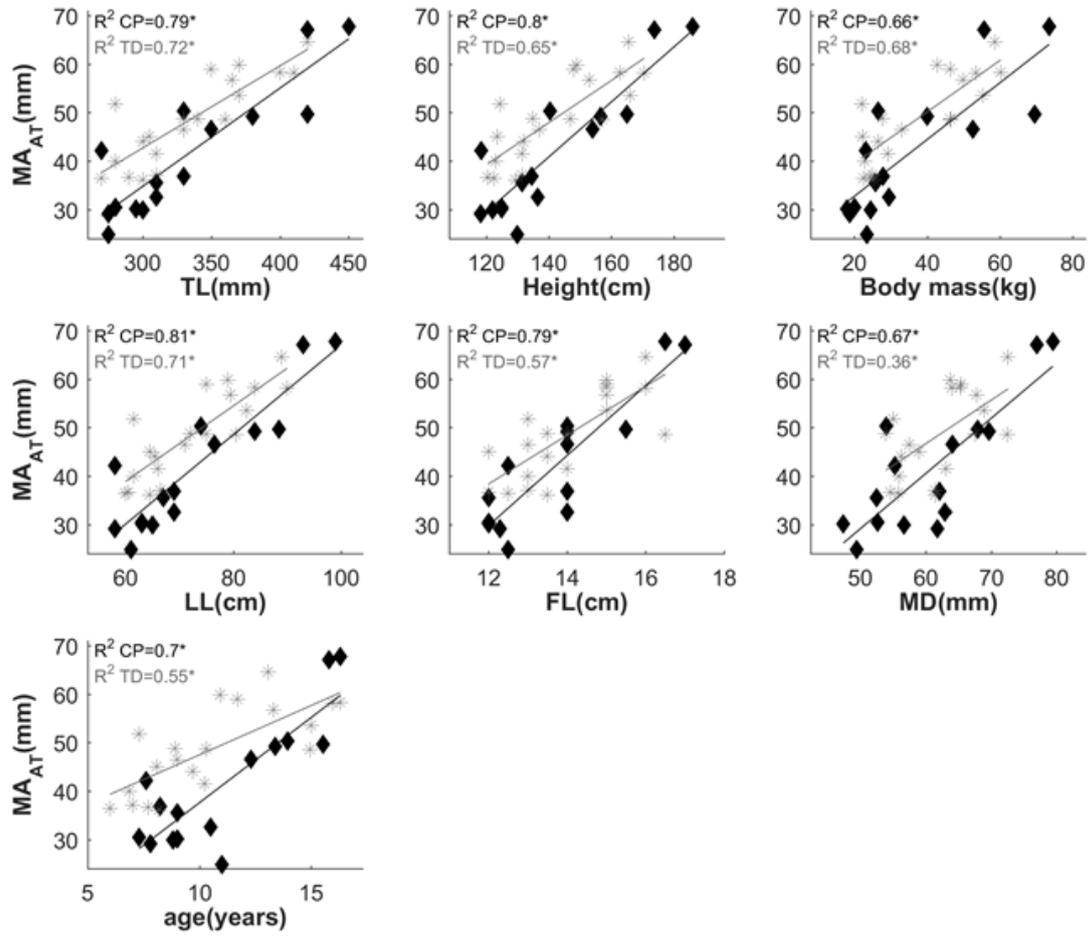


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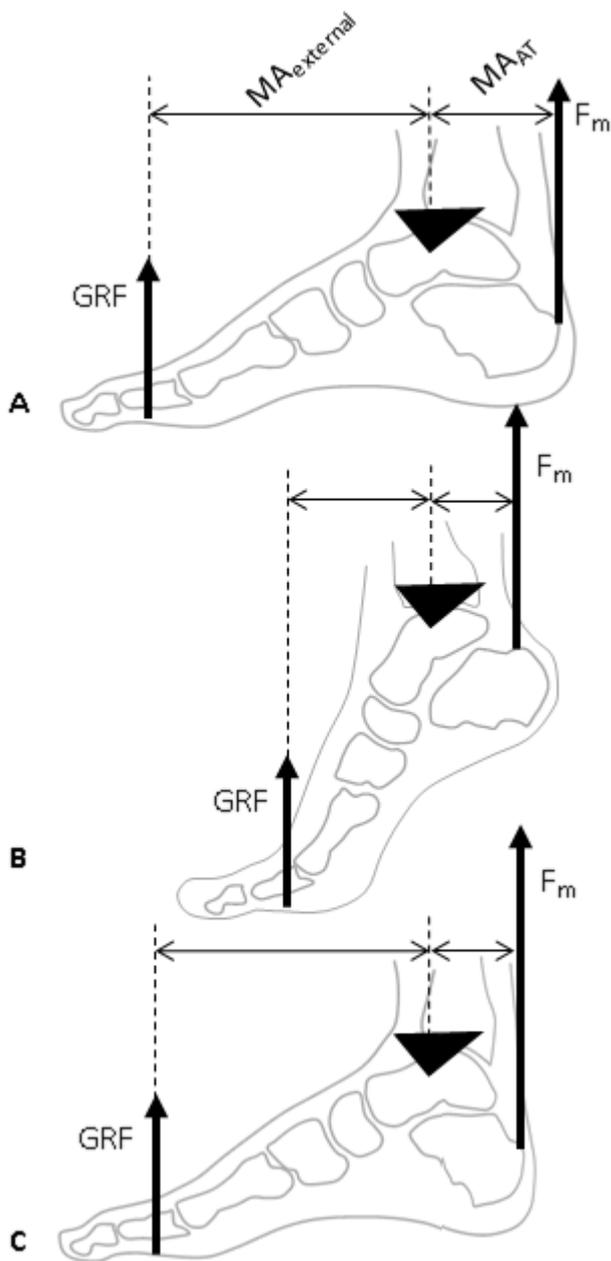
figure 1



415
416 **figure2**

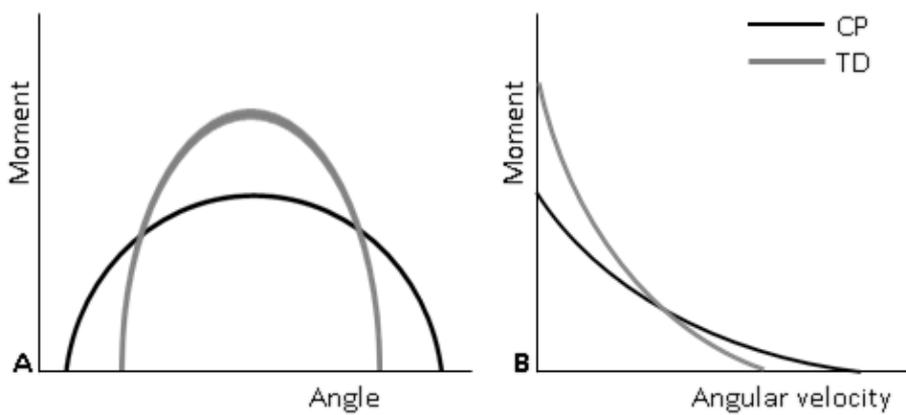


417
418 **figure3**



419

figure4



420

figure5