Not all brawn, but some brain. Strength gains after training alters kinematic motor abundance in hopping

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Background. The effects of resistance training on a muscle's neural, architectural, and mechanical properties are well established. However, whether resistance training can positively change the coordination of multiple motor elements in the control of a well-defined lower limb motor performance objective remains unclear. Such knowledge is critical given that resistance training is an essential and ubiquitous component in gait rehabilitation. This study aimed to investigate if strength gains of the ankle and knee extensors after resistance training increases kinematic motor abundance in hopping.

Methods. The data presented in this manuscript represents the pooled group results of a sub-study from a larger project investigating the effects of resistance training on load carriage running energetics. 30 healthy adults performed self-paced unilateral hopping, and strength testing before and after six weeks of lower limb resistance training. Motion capture was used to derive the elemental variables of planar segment angles of the foot, shank, thigh, and pelvis, and the performance variable of leg length. Uncontrolled manifold analysis (UCM) was used to provide an index of motor abundance (IMA) in the synergistic coordination of segment angles in the stabilization of leg length. Bayesian Functional Data Analysis was used for statistical inference, with a non-zero crossing of the 95% Credible Interval (CrI) used as a test of significance.

Results. Greater ankle strength significantly increased IMA, whilst greater knee strength decreased IMA, in the periods surrounding the first and last 25% of hop stance. For example, at 25% hop stance, a 1 Nm/kg increase in ankle extensor strength increased IMA by 0.48 (95% CrI 0.16 to 0.58), and a similar increase in knee extensor strength decreased IMA by -0.55 (95% CrI -0.74 to -0.35). Around mid-stance, only knee extensor gains predicted an increase in IMA.

Discussion. Resistance training not only improves strength, but also the structure of coordination in the control of a well-defined motor objective. The role of resistance training on motor abundance in gait should be investigated in patient cohorts, other gait patterns, and its translation into functional improvements.

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2 abundance in hopping.

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19   larger project investigating the effects of resistance training on load carriage running energetics.

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21   six weeks of lower limb resistance training. Motion capture was used to derive the elemental

22   variables of planar segment angles of the foot, shank, thigh, and pelvis, and the performance

23   variable of leg length. Uncontrolled manifold analysis (UCM) was used to provide an index of

24   motor abundance (IMA) in the synergistic coordination of segment angles in the stabilization of

25   leg length. Bayesian Functional Data Analysis was used for statistical inference, with a non-zero

26   crossing of the 95% Credible Interval (CrI) used as a test of significance.

27   **Results.**

28   Greater ankle strength significantly increased IMA, whilst greater knee strength decreased IMA,

29   in the periods surrounding the first and last 25% of hop stance. For example, at 25% hop stance,

30   a 1 Nm/kg increase in ankle extensor strength increased IMA by 0.48 (95% CrI 0.16 to 0.58),

31   and a similar increase in knee extensor strength decreased IMA by -0.55 (95% CrI -0.74 to -

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33   **Discussion.**

34   Resistance training not only improves strength, but also the structure of coordination in the

35   control of a well-defined motor objective. The role of resistance training on motor abundance in

36   gait should be investigated in patient cohorts, other gait patterns, and its translation into

37   functional improvements.

38   **Keywords:** Resistance training; Spring-mass model; Uncontrolled Manifold; Synergy

39

INTRODUCTION

Regular participation in walking and running has important health benefits (Lee et al. 2014), and

is commonly undertaken along irregular surfaces. Normally, humans have no problems

maintaining dynamic postural control and energy efficiency during gait despite these surface

irregularities, ensuring a smooth center of mass (COM) trajectory. Excessive COM trajectory

disturbance in gait can be energetically costly and potentially destabilizing to postural control

(Andrada et al. 2013; Geyer et al. 2006).

Perturbation to the COM trajectory can be minimized over irregular surfaces by adjusting the

length of a simplified virtual leg (henceforth termed as leg), spanning the COM to the center of

pressure (COP) (Andrada et al. 2013; Geyer et al. 2006). Leg length is regulated by four major

segments (foot, shank, thigh, and pelvis), along which flexion-extension occurs. The excess of

segments required to control a single leg, means that the body has an abundance of solutions to

flexibly combine segment angles to achieve the same leg length (Auyang et al. 2009). Greater

motor abundance in leg length regulation affords the body greater adaptability to rapidly react to

irregular surfaces to minimize COM trajectory perturbation. In the context of quantifying motor

abundance in leg length regulation, the Uncontrolled Manifold (UCM) analysis has been used to

investigate the motor control of unilateral hopping (Auyang et al. 2009). UCM provides a ratio

of two variances: one where the variance in angles (motor elements) does not change leg length

(performance variable), to a variance in angles which changes leg length (Auyang et al. 2009).

The manifestation of normal abundance in motor task may depend on the task's physical demand

relative to an individual's physiological strength capacity (Greve et al. 2013; Olafsdottir et al.

2008; Park et al. 2015; Shim et al. 2008; Yen & Chang 2010). Greater motor abundance may

emerge when the task's relative physical demand increases (Greve et al. 2013). For example,

63   older adults with lower maximal strength have non-significantly greater motor abundance in sit-

64   to-stand compared to younger adults with greater maximal strength (Greve et al. 2013). When an

65   external load is added to walking, there was a significant increase in the motor abundance of

66   joint angle co-variation in the control of the COM trajectory in the frontal plane, and a non-

67   significant increase in abundance in the control of the COM trajectory in the sagittal plane (Qu

68   2012). It is reasonable to expect that if one muscle is operating near its physiological limit,

69   additional muscles would be recruited to achieve successful performance.

70   In contrast, prospective resistance training studies of the upper limb (Olafsdottir et al. 2008; Park

71   et al. 2015; Shim et al. 2008) demonstrated that greater wrist and finger strength was associated

72   with greater abundance in finger force coordination tasks. Resistance training may augment

73   motor abundance by increasing reciprocal inhibition (Geertsen et al. 2008), of co-varying muscle

74   groups via heteronomous spinal pathways; increasing the role of bi-articular muscles in inter-

75   segmental kinematic co-variation (Cleather et al. 2015); and increasing the number of muscle

76   modes available for co-variation (Hashiguchi et al. 2016).

77   Although prospective study designs (Olafsdottir et al. 2008; Park et al. 2015; Shim et al. 2008)

78   already provide a higher level of evidence base than a cross-sectional design (Greve et al. 2013;

79   Qu 2012), the relationship between physiological strength and motor abundance, may still have

80   been confounded by other factors. First, different mathematical formulation of the variance ratios

81   of motor abundance between studies may have contributed to the conflicting evidence (see

82   differences between (Olafsdottir et al. 2008) and (Greve et al. 2013)). Second, differences may

83   lie in the hierarchical level of analysis as it pertains to the neural control of motor abundance.

84   Greve et al. (2013) investigated the covariation of joint-level kinematics to whole-body

85   performance variables, such as ground reaction force. The analysis by Greve et al. (2013) thus

86   did not consider an intermediary level of hierarchical control – that is in the stabilization of limb-

87   level performance variables (Toney & Chang 2016). In contrast, Olafsdottir et al. (2008)

88   investigated the covariation of limb-level (finger) force in the stabilization of the total force

89   generated by four fingers. To this end, a prospective study design which quantifies lower limb

90   motor abundance within a hierarchical control framework, would increase the evidence base

91   behind using resistance training to improve motor abundance.

92   Resistance training is an essential component in gait rehabilitation (Papa et al. 2017). Whether a

93   gain in physiological strength capacity benefits or harms motor abundance is an essential

94   question to answer, as it directly implicates the role of resistance training in gait rehabilitation.

95   The aim of this study was to investigate if lower limb strength gains after resistance training

96   influenced lower limb motor abundance. Hopping represents an excellent model of forward gait

97   patterns to fulfill the present study's aim. First, lower limb spring-mass dynamics in hopping is

98   present in walking and running (Geyer et al. 2006). Second, leg length is a regulated

99   performance variable in hopping using UCM analysis (Auyang et al. 2009). Given that leg length

100 mechanics contributes to COM trajectory (Moritz & Farley 2003), greater motor abundance in

101 leg length stabilization in hopping may translate into more available motor solutions to minimize

102 COM trajectory perturbation when walking or running over irregular surfaces. Third, normal

103 inter-segmental kinematic and kinetic coordination in hopping, quantified using UCM and vector

104 coding, varies depending on the task's relative physical demand (Auyang et al. 2009; Smith et al.

105 2014; Yen & Chang 2010), Similar to the effects of finger muscle strengthening on finger

106 pressing motor abundance (Olafsdottir et al. 2008), the hypothesis of this study was that greater

107 strength gains after resistance training would increase kinematic motor abundance in leg length

108 regulation during hopping.

MATERIALS AND METHODS.

Study design, participants

The data presented in this manuscript represents the pooled group results of a sub-study from a larger project investigating the effects of resistance training on load carriage running energetics (Liew et al. 2017). Thirty healthy active adults were recruited for this study (16 male, 14 female, mean (standard deviation) age of 30.35 (9.11) years, mass of 69.13 (12.65) kg, height of 1.72 (0.76) m). This study was approved by the Curtin University Human Research Ethics Committee (RD-41-14). Informed written consent was sought and gained prior to study enrolment.

Intervention

The two training programs were developed to improve load carriage running energetics (Table S1 in supplementary material). One group performed "conventional" heavy-resistance isoinertial training on the bilateral leg press, unilateral calf raises, and lunge exercises. These exercises have been routinely adopted in conventional load-carriage military training (Knapik et al. 2012). The other group performed "load carriage specific" resistance training targeting the specific biomechanical requirements of load carriage running (Liew et al. 2017). Exercises in this group comprised of externally loaded single-leg hopping to increase leg stiffness, countermovement jumps to increase knee power generation, and hip flexor pull to increase pre-swing running energetics (Liew et al. 2017). Greater leg stiffness, knee power generation, and pre-swing hip energetics were previously shown to be required to sustain constant running velocity during load carriage (Liew et al. 2016; Silder et al. 2015). Despite the differences between the training programs, the present study was only interested in accounting for the between time (pre-post) change in strength (ankle extensor = mean increase 0.34 Nm/kg [95% Confidence Interval (CI)

131   0.25 to 0.42 Nm/kg]; knee extensor = mean increase 0.24 Nm/kg [95% CI 0.11 to 0.37 Nm/kg])

132   (Liew et al. 2017), in predicting alterations in hopping motor abundance.

133   **Three dimension motion capture on hopping**

134   Participants performed unilateral hopping, on both sides, at a self-selected frequency lasting

135   approximately 15s. The only instruction provided was to hop at a "comfortable pace". In the post

136   hoc analysis stage, only hops maintained within 10% of the individual's mean hop frequency

137   was kept for further analysis (termed as successful trials). This 10% frequency window was

138   deemed appropriate given that a previous study reported a variation of up to 20 % for adults

139   hopping at their preferred frequency (Beerse & Wu 2016). A between side standing rest period of

140   one minute was provided. An 18 camera motion capture system (Vicon T-series, Oxford Metrics,

141   UK) (250 Hz), with synchronized in-ground force plates (AMTI, Watertown, MA) (2000 Hz)

142   were used to collect marker trajectories and force data (Vicon Nexus, v2.3, Oxford Metrics, UK).

143   Force data were used to detect initial contact and toe-off, with a 20 N vertical force threshold

144   used. The marker placements and biomechanical model were based on a previously work (Liew

145   et al. 2016). Marker trajectories were low pass filtered at 12 Hz (zero lag, 4th order, Butterworth).

146   Global optimization performed in Visual 3D (C-motion, Germantown, MD) was used to derive

147   the model's kinematics.

148   **Isokinetic strength measurement**

149   Isokinetic concentric strength testing of the bilateral knee and ankle extensors was performed in

150   a dynamometer (HUMAC NORM, Computer Sports Medicine Inc., Stoughton, MA), collecting

151   data at 100 Hz and set up according to the manufacturer's guidelines (Liew et al. 2017). For each

152   muscle group tested, participants first performed 10 repetitions of warm-up contractions at 90°/s,

153   and two sets of six maximal concentric-concentric contractions at 60°/s. Each set was

154   interspersed with one minute of seated rest in-situ. Between muscle group and side rest periods

155   of three minutes were provided.

156   **Uncontrolled manifold analysis**

157   A modified sagittal plane forward kinematic model mapping segment angles to leg length used in

158   a previous study was adopted in the present study (Auyang et al. 2009) (see Figure S1 in

159   supplemental for the kinematic model). Leg length was presently defined by the vector between

160   the centre of pressure (COP) to the proximal end of the pelvic segment, instead of the toe and

161   anterior superior iliac spine markers, respectively (Auyang et al. 2009). The foot, shank, thigh,

162   and pelvic segments were defined by the line vectors between 1) COP to ankle joint centre, 2)

163   ankle to knee joint centre, 3) knee to hip joint centre, and 4) hip joint to proximal end of pelvis.

164   All segment angles and leg lengths were time-normalized to 100 data points in the stance period

165   for UCM analysis.

166   The UCM analysis was carried out using a previously published method (Auyang et al. 2009),

167   for each of the 100 stance data points.

168
$$NGEV = \frac{trace(orth\,(J^t)^t.C.orth(J^t))}{d}...(1)$$

169
$$GEV = \frac{trace(null\,(J)^t.C.orth(J))}{n-d}...(2)$$

170
$$IMA = \frac{GEV - NGEV}{GEV + NGEV}...(3)$$

171   where non-goal equivalent variance (NGEV) represents the variance of all segment angle

172   combinations which deviates leg length; goal equivalent variance (GEV) represents the variance

173 of all segment angle combinations which does not deviate leg length; index of motor abundance

174 (IMA) where an IMA > 0 represents variation in segment angles which were minimizing leg

175 length variation (i.e. motor abundance), and an IMA < 0 represents variation in segment angles

176 which were maximising leg length variation (Auyang et al. 2009), J is the Jacobian matrix

177 mapping infinitesimally small changes in segment angles to changes in leg length; C is the co-

178 variance matrix in the deviation of the segment angles from the mean reference segment angles

179 at each datum; d is the degree of freedom in the performance variable (d = 1 in this study); and n

180 is the degree of freedom in the elemental variables (n = 4).

181 **Statistical analysis**

182 Descriptive scalar variables of post-pre change in hopping frequency and stance duration, and

183 baseline (pre-training) waveform variables of leg length, foot, shank, thigh, and pelvic segment

184 angles, IMA, GEV, and NGEV were reported. The dependent variable was the between time

185 change in waveform IMA. The predictor variables were the between time change (post-pre) in

186 ankle and knee strength, and the regression coefficients were adjusted for two covariates: 1)

187 change (post-pre) in hopping frequency, and 2) side (right vs left) were included in the statistical

188 model. Bayesian regression functional analysis was performed in R software (Goldsmith &

189 Kitago 2016). Recent investigations in sports science have advocated the avoidance of

190 frequentist null-hypothesis significance testing, and instead to focus on estimating the

191 probabilities associated with observing an effect size. Fixed effect parameters for ankle and knee

192 strength, frequency, and side, and non-parametric smooth functions (modelled with 12 B-splines)

193 were estimated using a Gibbs sampler with a burn-in of 1000 and drawing 11000 inference

194 samples. The residual covariance structure was estimated using Bayesian functional principle

195 components. A significant effect was defined by a non-zero crossing of the Bayesian 95%

196 credible interval (CrI).

RESULTS

197

198 Five participants were excluded due to the low number of successful hopping trials (< 20 trials)

199 that has been recommended for UCM analysis (Latash et al. 2010) (Figure 1). Baseline

200 differences between the included and excluded participants in baseline characteristics were

201 small: mean difference in age of 5 years, height of 3.5 cm, weight of 1.9 kg, ankle strength of

202 0.14 Nm/kg, and knee strength of 0.2 Nm/kg. The difference in the mean ankle and knee beta

203 coefficients between a complete case analysis (n = 30) over the present analysis (n=25) were

204 small, at 0.04 and 0.08, respectively. Baseline hopping kinematics, IMA, GEV, NGEV are

205 reported in Figure 2 and 3. The mean (standard deviation) change in hopping frequency was a

206 0.13 (0.3) Hz increase and change in stance duration was a 0.01 (0.04) s decrease post-testing,

207 relative to a baseline of 2.26 (0.25) Hz and 0.30 (0.03) s, respectively.

208 For simplicity of reporting, only effects at a discrete hop phase within a statistically significant

209 temporal period are reported here. At 25% hop stance, a 1 Nm/kg increase in ankle extensor

210 strength increased IMA by 0.48 (95% CrI 0.16 to 0.58), and a 1 Nm/kg increase in knee extensor

211 strength decreased IMA by -0.55 (95% CrI -0.74 to -0.35) (Figure 4). At 55% stance, a 1 Nm/kg

212 increase in knee extensor strength increased IMA by 0.25 (95% CrI 0.001 to 0.49) (Figure 4). At

213 75% hop stance, a 1 Nm/kg increase in ankle extensor strength reduced IMA by -0.34 (95% CrI -

214 0.58 to -0.13), and a 1 Nm/kg increase in knee extensor strength increased IMA by 0.30 (95%

215 CrI 0.07 to 0.54) (Figure 4). At 95% hop stance, a 1 Nm/kg increase in ankle extensor strength

216   increased IMA by 0.24 (95% CrI 0.03 to 0.45), and a 1 Nm/kg increase in knee extensor strength

217   decreased IMA by -0.81 (95% CrI -1.05 to -0.58) (Figure 4).

DISCUSSION

219   Leg length regulation is a strategy of coping with irregular surfaces to minimize disturbance to

220   the COM trajectory during gait (Andrada et al. 2013; Geyer et al. 2006). Normally, leg length

221   regulation is achieved by harnessing segmental kinematic motor abundance (Auyang et al. 2009).

222   Even though resistance training has been typically prescribed to treat gait impairments, there is

223   uncertainty as to the relationship between physiological strength capacity and normal motor

224   abundance. This poses a dilemma as to whether resistance training benefits or harms gait motor

225   control rehabilitation. In this study, we prospectively investigated if lower limb strength gains

226   after resistance training, predicted a change in IMA during a simple model of spring-mass gait -

227   unilateral hopping. In partial agreement with our hypothesis, greater strength gains predicted an

228   increase in IMA, but this effect was dependent on the muscles being strengthened. In addition,

229   the effects of ankle strength gained on IMA was opposite to that of knee strength gains.

230   The increase in kinematic motor abundance with a gain in ankle extensor strength prior to mid-

231   stance and toe-off of hopping, was consistent with the findings of previous resistance training

232   studies of the upper limb (Olafsdottir et al. 2008; Park et al. 2015; Shim et al. 2008). The

233   mechanisms linking strength gains to motor abundance improvements was not investigated in the

234   present study, but may speculatively involve mechanical and neural factors. The bi-articular

235   gastrocnemius is mechanically capable of plantar flexing the foot while flexing the knee

236   (Cleather et al. 2015). Greater gastrocnemius strength could augment inter-segmental kinematic

237   co-variation, increasing motor abundance during hopping. Resistance training has also been

238   shown to increase reciprocal inhibition of antagonistic muscles within a joint muscle pair

239   (Geertsen et al. 2008). However, no studies to the authors' knowledge have directly investigated

240   the influence of resistance training on heteronomous reflex pathways, which would enable inter-

241   muscular co-variation and facilitate hopping kinematic motor abundance.

242   It was previously suggested that greater motor abundance will emerge in tasks with greater

243   relative physical demand (Greve et al. 2017; Greve et al. 2013), which contradicts the present

244   findings. It may be that the relationship between physical demand and motor abundance is non-

245   linear with potentially plateauing effects. Both physiological weakening and strengthening may

246   augment motor abundance depending in part on the task's absolute demand on the participants,

247   and the capacity to use available motor elements. Wang et al. (Wang et al. 2017) reported that

248   older adults have preserved muscle motor abundance but were more delayed at their recruitment

249   during rapid balance recovery, than younger adults. The tasks used by Greve and Colleagues

250   were either much slower (Greve et al. 2013), or required a combination of low muscular force

251   and fast movement speed (Greve et al. 2017). It is plausible that the speed-force demands in

252   previous studies were low (Greve et al. 2017; Greve et al. 2013), such that muscle groups had

253   sufficient time to stabilize the performance variable(s). In addition, if a muscle is operating at its

254   physiological limit, it can no longer compensate for the reduction in activation of other muscles.

255   In this instance, co-variation may still occur but only between muscles with adequate

256   physiological strength reserve. The relationship between task demand and motor abundance may

257   be better understood by investigating abundance at the level of muscle activations, including

258   UCM analysis in a reduced subset of motor elements (Toney & Chang 2016).

259   The period surrounding mid-stance in hopping is critical of leg length regulation for peak

260   muscular force minimization (Auyang et al. 2009), which minimizes the energy expenditure and

261   joint contact loads during hopping. It was surprising that knee extensor strength, but not ankle

262   extensor strength gain, had augmenting effects on kinematic motor abundance between 50% to

263   75% stance. The foot segment angle around mid-stance was nearly invariant (Figure 1) (Joao et

264   al. 2014). If the foot functions as a punctum fixum around mid-stance (Joao et al. 2014), the

265   gastrocnemius is only able to flex and extend the thigh segment, without compensatory foot

266   kinematics to stabilize overall leg length. The invariant foot-segment angle may instead shift the

267   joint-level mediator of leg length stabilization to the knee. In contrast, greater knee extensor

268   strength reduced abundance for leg length control in the periods surrounding initial contact and

269   toe-off. It may be that the influence of knee extensor strength gain on kinematic abundance was

270   shifted to the control of leg orientation (angle between the leg and ground) (Auyang et al. 2009).

271   Leg orientation at initial contact may determine the overall position relative to the COM in

272   stance, and at toe-off as it influence flight-phase ground clearance.

273   The reduction in kinematic motor abundance predicted by an increase in knee extensor strength

274   prior to mid-stance and toe-off differed from a study investigating walking in individuals with

275   and without knee osteoarthritis (OA) (Tawy et al. 2018). Several reasons could account for the

276   disagreement. Tawy et al. (Tawy et al. 2018) did not directly quantify the relationship between

277   knee extensor strength and motor abundance. The occurrence of knee OA is associated with a

278   range of neuromuscular deficits (Mills et al. 2013), and the importance of knee extensor strength

279   to motor abundance cannot be ascertained from a between-groups comparison. Second, Tawy et

280   al. (Tawy et al. 2018) used COM trajectory, while the present study used leg length, as the

281   performance variable for UCM analysis. It must be emphasized that using both the COM and leg

282   length as performance variables are equally valid. The organization of motor control may involve

283   a hierarchical structure (Latash 2010), where segment-level variation serve to stabilize limb-level

284 outcomes, and inter-limb variation stabilizes whole-body outcomes. Thus, the present study

285 focused only on limb-level motor control, while Tawy et al. (Tawy et al. 2018) performed UCM

286 analysis across two layers of hierarchical control.

287 Several aspects of the present study's methodology need to be discussed in lieu of differences in

288 reported IMA of the present study, with that of a previous work (Auyang et al. 2009). First, the

289 number of hop cycles included per participant ranged from 20 to 57 cycles. In contrast, Auyang

290 et al. (Auyang et al. 2009) used 170 cycles for UCM calculation, which may explain the

291 difference in IMA values between studies. Second, leg length was defined starting from the COP

292 in the present study, but from the toe marker in Auyang et al. (Auyang et al. 2009). COP

293 accuracy may be reduced when the magnitude of the GRF is small, which could explain the

294 differences in IMA between the present study and Auyang et al. (Auyang et al. 2009) during the

295 periods surrounding initial contact and toe-off. However, the effective leg length during human

296 locomotion may be more accurately defined from the point of ground force application,

297 compared to the fixed toe-marker (Coleman et al. 2012). Despite this difference in leg length

298 definition, the overall shape of the IMA reported in this study was similar to Auyang et al.

299 (Auyang et al. 2009).

300 Previous studies provided evidence for the benefit of resistance training on finger force motor

301 abundance (Olafsdottir et al. 2008; Park et al. 2015; Shim et al. 2008), and the results of the

302 present study extends the evidence for the same benefit to the lower limb. By increasing motor

303 abundance to stabilize leg length in hopping, resistance training may increase the adaptability of

304 forward gait patterns over irregular surfaces. It is likely that different gait patterns require

305 different joint-level and limb-level strengthening to benefit kinematic motor abundance, and this

306 should be investigated in future studies. A limitation of this study was that the analysis predicting

307 motor abundance from alterations in strength gains were analyzed using a prospective, pre-post

308 design. However, we reduced the confounding factor of repeated measurement, by only

309 including the effects of strength changes into the statistical model. A second limitation of this

310 study was that the influence of strength gains on kinematic abundance was analyzed in healthy

311 individuals. This limitation may in fact be a strength, as we were able to isolate the investigation

312 of IMA changes to strength changes.

313 **CONCLUSIONS**

314 In addition to the well-known effects on a muscle's neural, architectural, and mechanical

315 properties, resistance training also influences the coordination of multiple motor elements in the

316 control of a well-defined motor performance objective. The benefits of strength gain on motor

317 abundance was dependent on the site of muscle strengthened and the phase of gait. The role of

318 resistance training on motor abundance should be investigated in patient cohorts, other gait

319 patterns, as well as its translation into functional improvements.

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323 The results of this study are presented clearly, honestly, and without fabrication, falsification, or

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419

Figure 1. CONSORT Diagram

Figure 1

Assessed for eligibility
(n = 50)

Excluded:
- Not meeting inclusion criteria
  (n= 3)
- Declined to participate (n = 17)

2 week preparatory phase
(n = 32)

Baseline biomechanics assessments (n=30): Hopping

Randomized (n=30)

Allocation (week 0)

Conventional training group (n = 16)
Received allocated intervention (n = 16)

Load carriage specific training group
(n = 14)
Received allocated intervention (n = 14)

Final biomechanics assessments. Follow-Up (week 7)

Lost to follow-up (n = 0)

Discontinued intervention (n = 0)

Lost to follow-up (n = 0)

Discontinued intervention (n = 0)

Pooled analysis

Analysed (n = 25)
Excluded from analysis (n = 5)

Figure 2. Baseline mean (standard deviation as error clouds) of leg length (m) and segment angles (°)
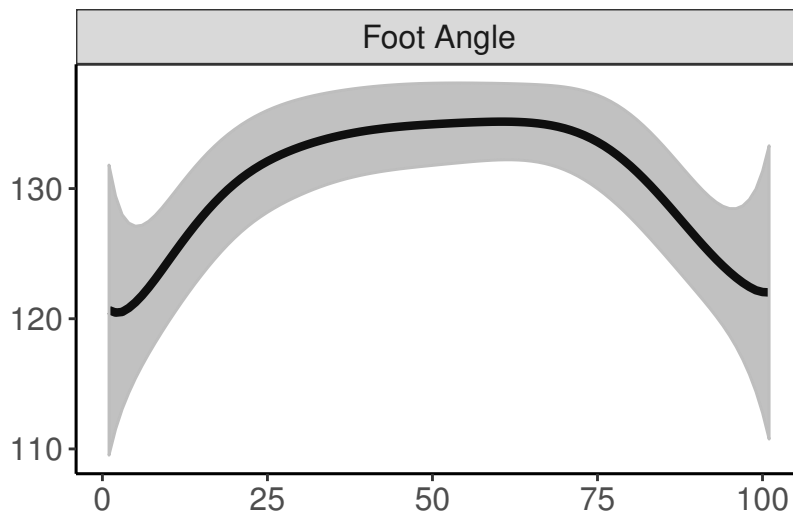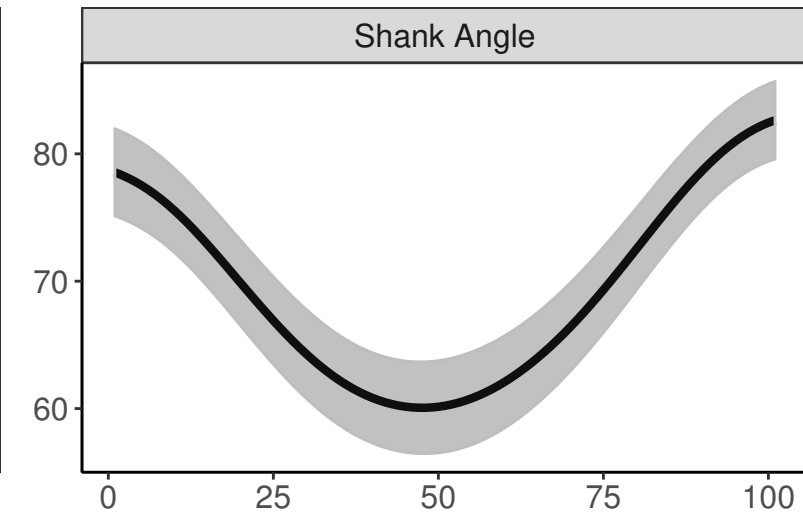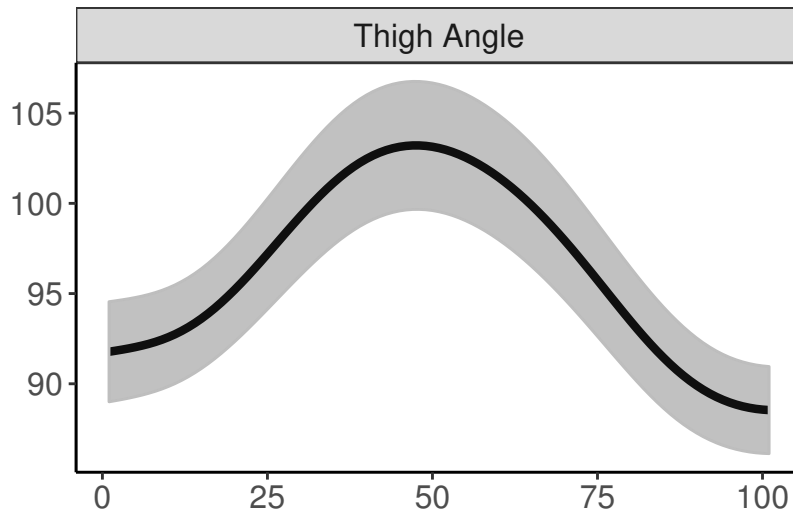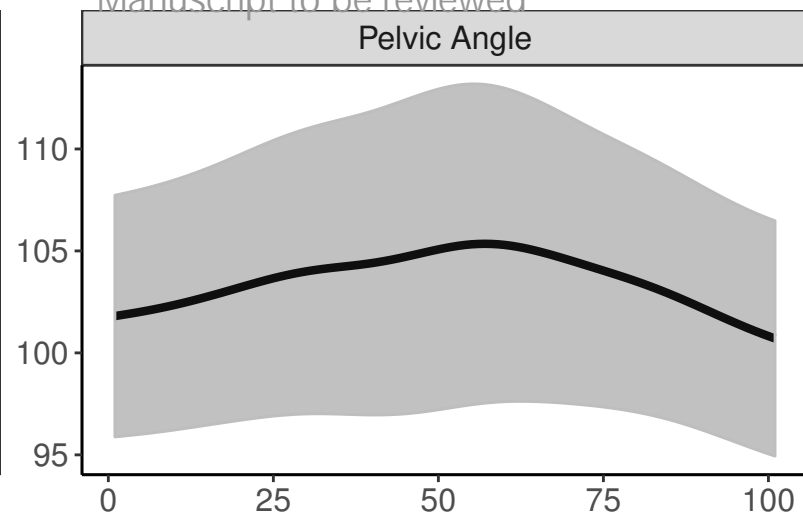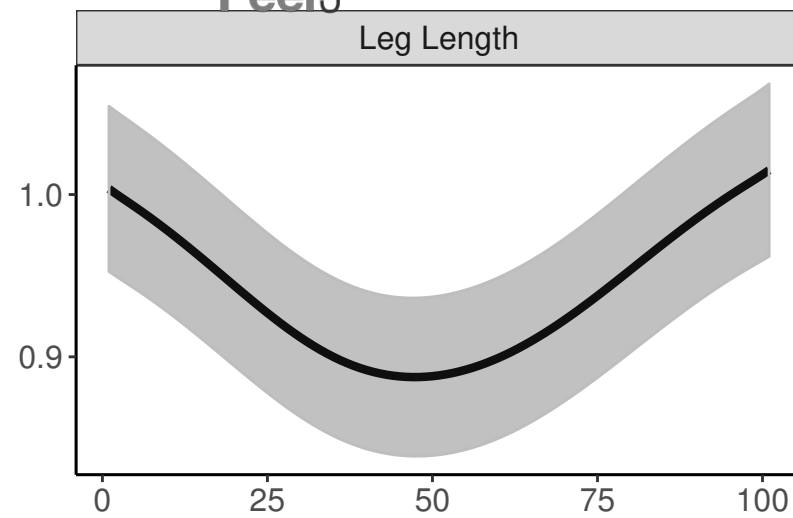
Figure 3. Baseline mean (standard deviation as error clouds) of Index of Motor Abundance (IMA), Non-Goal Equivalent Variance (NGEV) and Goal Equivalent Variance (GEV).
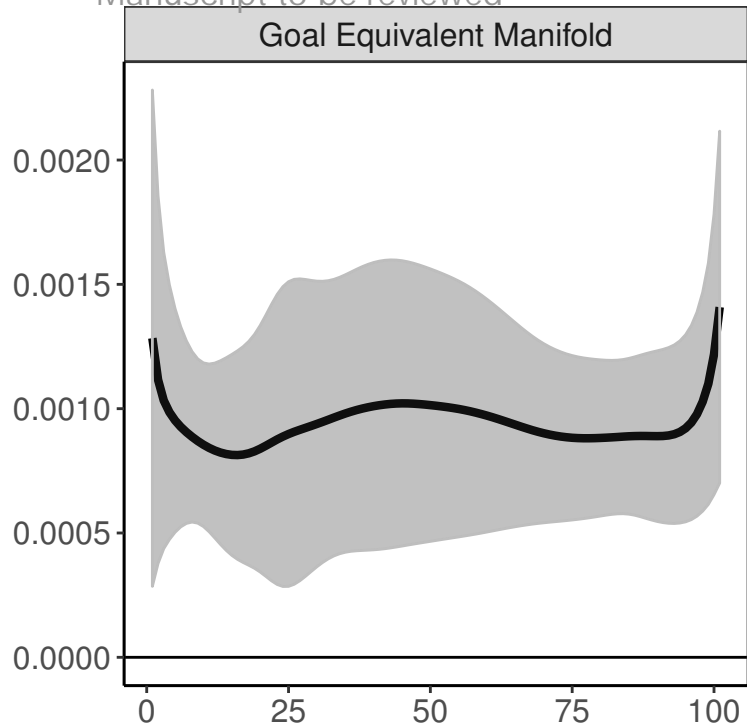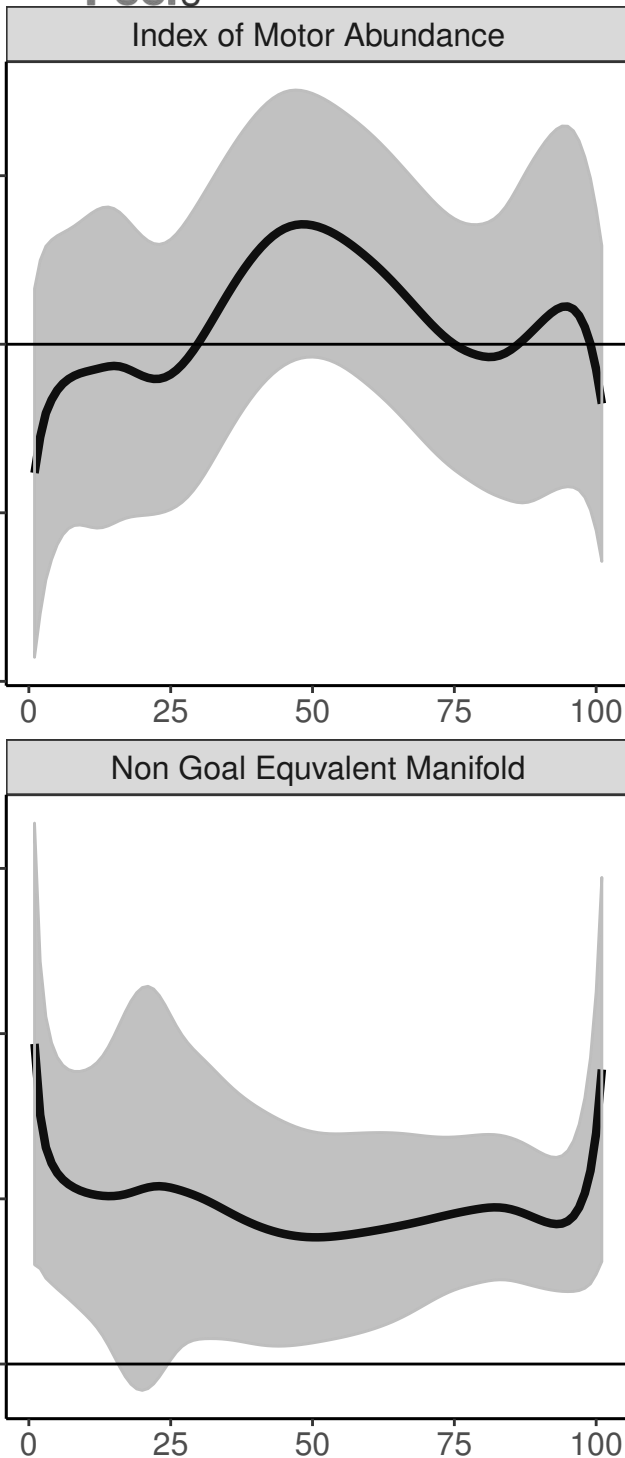
Figure 4. Mean (95% Credible Interval as error clouds) of beta coefficient of 1 Nm/kg increase in ankle extensor strength (left) and knee extensor strength (right).