# Relationship between intended force and actual force: comparison between athletes and sedentary individuals

**Alex Rizzato** [1], **Giovanni Cantarella** [2], **Elisa Basso** [1], **Antonio Paoli** [1], **Luca Rotundo** [1], **Patrizia Bisiacchi** [2], **Giuseppe Marcolin** [Corresp. 1]

[1] Department of Biomedical Sciences, University of Padua, Padua, Italy

[2] Department of General Psychology, University of Padua, Padua, Italy

Corresponding Author: Giuseppe Marcolin
Email address: giuseppe.marcolin@unipd.it

This study aimed to investigate whether athletes (ATL) and sedentary (SED) individuals had similar accuracy in matching intended to actual force during ballistic (BAL) and tonic (TON) isometric contractions. A cross-sectional study in which forty subjects were enrolled and divided into ATL (n=20; 22.4±2.3yrs; 73.2±15.7kg; 1.76±0.08m) and SED (n=20; 24.6±2.4yrs; 68.2±15.0kg; 1.73±0.1m) groups. The isometric quadriceps strength was measured with a load cell applied to a custom-built chair. For each condition, subjects performed first three maximal voluntary isometric contractions (MVIC) as reference. Then, subjects had to match for three trials the intended force intensities (i.e., 25%, 50%, and 75% of the MVIC) without any external feedback. The accuracy (AC) was calculated as the difference in percentage between the intended and the actual force. A Likert scale was administered for each trial to assess the subjective matching between the intended and the actual force. Statistical analysis showed that ATL group was more accurate (p < 0.001) than the SED group, while the AC (p < 0.001) was lower when the force intensities increased, independently from the group. Moreover, significantly greater AC (p< 0.001) and subjective matching were found in BAL and TON contractions, respectively. These results suggest that: (i) sports practice could enhance muscle recruitment strategies increasing the accuracy in the isometric task; (ii) protective mechanisms or proximity to the levels of daily living forces could account the decrement of accuracy at high force intensities; (iii) different control systems act in modulating BAL and TON contractions.

1 **Relationship between intended force and actual force: comparison between athletes and**

2 **sedentary individuals**

3 Alex Rizzato[1], Giovanni Cantarella[2], Elisa Basso[1], Antonio Paoli[1], Luca Rotundo[1], Patrizia

4 Bisiacchi[2], Giuseppe Marcolin[1*].

5 [1]*Department of Biomedical Sciences, University of Padova, Italy.*

6 [2]*Department of General Psychology, University of Padova, Italy.*

8 *Correspondence:

9 Giuseppe Marcolin PhD

10 Department of Biomedical Sciences, University of Padova, Italy,

11 Tel: 049-8275869

12 Via Marzolo, 3, 35131 Padova, Italy.

13 Email: giuseppe.marcolin@unipd.it

14 ORCID iD: 0000-0002-2768-3257

## Abstract

23  This cross-sectional study aimed to investigate whether athletes (ATL) and sedentary (SED)

24  individuals had similar accuracy in matching intended to actual force during ballistic (BAL) and

25  tonic (TON) isometric contractions. A cross-sectional study in which forty subjects were enrolled

26  and divided into ATL (n=20; 22.4±2.3yrs; 73.2±15.7kg; 1.76±0.08m) and SED (n=20;

27  24.6±2.4yrs; 68.2±15.0kg; 1.73±0.1m) groups. The isometric quadriceps strength was measured

28  with a load cell applied to a custom-built chair. For each condition, subjects performed first three

29  maximal voluntary isometric contractions (MVIC) as reference. Then, subjects had to match for

30  three trials the intended force intensities (i.e., 25%, 50%, and 75% of the MVIC) without any

31  external feedback. The accuracy (AC) was calculated as the difference in percentage between the

32  intended and the actual force. A Likert scale was administered for each trial to assess the subjective

33  matching between the intended and the actual force. Statistical analysis showed that ATL group

34  was more accurate (p < 0.001) than the SED group, while the AC (p < 0.001) was lower when the

35  force intensities increased, independently from the group. Moreover, significantly greater AC (p<

36  0.001) and subjective matching were found in BAL and TON contractions, respectively. These

37  results suggest that: (i) sports practice could enhance muscle recruitment strategies increasing the

38  accuracy in the isometric task; (ii) protective mechanisms or proximity to the levels of daily living

39  forces could account the decrement of accuracy at high force intensities; (iii) different control

40  systems act in modulating BAL and TON contractions.

41

42  **Keywords:** isometric strength; leg extension; maximal voluntary contraction; force modulation;

43  subjective perception.

44

45

46

**Introduction**

48   Intended force refers to muscle tension sensations experienced during contraction (Jones & Hunter,

49   1983). It results from a neuronal process influenced by two factors: the corollary discharge of the

50   central motor command (i.e., the motor signal informs the sensory system about the planned or

51   implemented action) and afferent feedback from the working muscles (Jones & Hunter, 1983;

52   Pageaux, 2016). Indeed, peripheral inputs from the neuromuscular spindles and Golgi tendon

53   organs provide information to higher centers about the in-place contraction (Carson, Riek &

54   Shahbazpour, 2002; Proske & Allen, 2019). Moreover, the cerebellum ensures movement accuracy

55   and sensory perception by communicating with the brain areas and sensory channels (Bhanpuri,

56   Okamura & Bastian, 2012).

57   Historically, to the extent of standardizing the means of rating the perceived effort at specific

58   muscular forces, scientific literature (Cooper et al., 1979; Jones & Hunter, 1982) focused on the

59   relationship between actual and intended force in different muscle groups. The work by Cooper

60   and colleagues (Cooper et al., 1979) suggested that a single motor performance, namely isometric

61   or dynamic contraction, can be perceived with remarkable precision by both small (e.g., adductor

62   pollicis) and large (e.g., quadriceps) muscle groups. However, a perceptual underestimation of

63   force might occur in larger muscle groups, more commonly involved in gross movements, when

64   lower levels of force are required, to accomplish fine movements (Jones & Hunter, 1982).

65   More recently, the scientific interest moved to deepen the relationship between actual and intended

66   force at different intensities of a maximal voluntary contraction (MVC). Indeed, in a motor task,

67   the force intensity is influenced by the recruitment and firing rate of the motor unit and by the type

68   of contraction (i.e., ballistic or tonic), (Miyamoto, Kizuka & Ono, 2020). Ballistic contractions are

69   performed with maximal velocity and acceleration, while tonic contractions generate a slow and

70   maintained force (Zher and Sale, 1994). Previous studies pointed out conflicting results on the

71   force intensities and the subjects' accuracy in matching intended and actual force. In detail, West

72   and colleagues showed that when subjects were asked to produce a specific force level during an

73   isometric knee-extension task (i.e., without MVC reference), they were more accurate at lower

74   intensities, whereas they overestimated the intended force in high-intensity contractions (West et

75   al., 2005). Similarly, Miyamoto and colleagues (Miyamoto, Kizuka & Ono, 2020) showed that the

76   intended force did not accurately match the target contraction without visual feedback, with a more

77   precise performance at high rather than low intensities. To the best of our knowledge, none of the

78   above-mentioned studies considered the subjects' sports experience as a potential influencing

79   variable in force modulation (i.e., ballistic and tonic) at different intensities (Baweja et al., 2009;

80   Miyamoto, Kizuka & Ono, 2019). Indeed, samples were scarcely described without considering

81   that physical activity level and sports experiences could have affected the results. In this regard,

82   athletes are likely to manage better physiological function, muscle contractions, and sports

83   demands than their sedentary counterparts (Thorstensson et al., 1977; Hagberg et al., 1988).

84   Moreover, team sports practice helps athletes more easily govern motor patterns than sedentary

85   individuals due to their higher ability to perform motor tasks under stressful conditions in open-

86   skill contexts (Cortis et al., 2009). Therefore, this study aimed to investigate whether athletes and

87   sedentary individuals had similar accuracy in matching the intended and the actual force during

88    ballistic and tonic contractions in an isometric leg extension task. In detail, hypothesizing that

89    sports practice could positively influence subjects' ability to modulate force, we expected that the

90    group of athletes could better exert force at the required percentage of the maximal effort.

91    **Materials & Methods**

92    **Subjects**

93    Forty young, healthy subjects between 18 and 35 years old (age: $23.5 \pm 2.6$ yrs; mass: $70.7 \pm 15.3$

94    kg; height: $1.74 \pm 0.08$ m) volunteered to participate in the study. They were divided into two

95    groups: sedentary (SED; n = 20; F = 13; $24.6 \pm 2.4$ yrs; $68.2 \pm 15.0$ kg; $172.8 \pm 9.60$ m) and élite

96    athletes (ATL; n = 20; F = 6; $22.4 \pm 2.3$ yrs; $73.2 \pm 15.7$ kg; $1.76 \pm 0.08$ m). At the time of

97    recruitment, the SED group had (i) no history of competitive sport practice and (ii) no current

98    practice of any physical activity. The ATL group currently practiced an individual (n=4 track and

99    field; n=1 canoeing; n=1 fencing; n=1 gymnastics) or team (n = 6 basket; n = 3 rugby; n = 2

100   volleyball; n = 2 soccer) sport discipline at a competitive level. The experimental protocol received

101   approval (HEC-DSB/05-21) from the Human Ethical Committee of the department of Biomedical

102   Sciences of the University of Padova and adhered to the principles of the Declaration of Helsinki.

103   All the subjects involved in the study were informed about the methods and aims of the study,

104   gave their written consent, and were free to renounce the study at any stage.

105

106   **Study design**

107   We outlined a cross-sectional design in which subjects were asked to perform isometric leg-

108   extension strength tests at different intensities (25%, 50%, and 75% of the MVC) without any

109   feedback. Two different muscle contractions were studied: tonic (TON) and ballistic (BAL). In the

110 TON condition, subjects reached the intended force level with a slow and maintained three-second

111 muscle contraction. Conversely, in the BAL condition, the intended force had to be reached

112 instantaneously. At a preliminary stage, the Waterloo Footedness-revised (WFQ-R) and Global

113 Physical Activity (GPAQ) questionnaires were administered to subjects to identify the dominant

114 leg for the execution of the tests and to estimate the subjects' physical activity level, respectively.

115 After each contraction, subjects were administered a Likert Scale to assess their self-perceived

116 accuracy in the strength task. Muscle contractions and the intensities within each type of

117 contraction were randomized.

118 **Isometric lower-limb strength**

119 The dominant lower limb strength was evaluated through an isometric voluntary quadriceps

120 contraction. The experimental setup consisted of a custom-built chair (**figure 1A**) instrumented

121 with a uni-axial load cell (MuscleLab, Ergotest Innovation, Stathelle, Norway) positioned three

122 centimeters above the lateral malleolus. The subjects performed the strength test seated with the

123 knee flexed at 90 degrees and secured to the chair with straps to minimize additional body

124 movements. Subjects were asked to keep their hands crossed over the chest for the whole test

125 duration. After a standardized warm-up (i.e., a 10-min walk on a treadmill at 5 km/h and 10

126 repetitions of half-squat exercise), each subject was familiarized with the experimental setup by

127 performing ten sub-maximal isometric quadriceps contractions with real-time visual feedback on

128 the level of the exerted force. Then, after a 5-minute rest, subjects performed the test without any

129 external feedback. Specifically, subjects were required to exert, for each of the two contractions

130 (i.e., BAL and TON), first the maximal voluntary isometric contraction (MVIC) and then the three

131 submaximal intensities (i.e., 25%, 50%, and 75% of the MVIC). Regardless of the condition and

132 the intensities, three trials and an in-between recovery of 40 seconds were set for each intensity.

133 In the BAL condition, the subjects were asked to reach as fast as possible the required submaximal

134 force intensity (**figure 1B**). Conversely, in the TON condition, the subjects manually triggered an

135 accelerometer synchronized with the force signal and defined the moment their actual force was

136 supposed to correspond to the intended force (**figure 1C**).

137

138 **Questionnaires**

139 *Waterloo Footedness Questionnaire-revised (WFQ-R).* The questionnaire contains 19 items (van

140 Melick et al., 2017). Twelve items are specifically addressed to determine limb dominance, and

141 subjects marked a preference (i.e., right or left limb) for the action indicated by each item. In detail,

142 subjects were required to mark with a double sign (+ +) whether they had an absolute preference

143 for a limb. Conversely, if they had a preference but could perform the action with both limbs, they

144 were asked to mark the preference with a single sign (+). Subjects marked both limbs with a single

145 sign if they had no preference. Finally, seven items assess the current and past injuries with a

146 "yes/no" answer.

147 *Global Physical Activity Questionnaire (GPAQ-2).* Before trials, each subject was administered

148 the GPAQ-2 to estimate the daily physical activity level (Bull, Maslin & Armstrong, 2009). With

149 16 items, GPAQ-2 covers several physical activity components, such as intensity, duration, and

150 frequency. It assesses the three domains in which physical activity is performed: (i) occupational

151 physical activity, (ii) transport-related physical activity, and (iii) physical activity during

152 discretionary or leisure time. The sum of the total Metabolic Equivalent (MET) minutes/week of

153 activity was computed for a typical week in each domain.

154 *Likert scale.* A single-item Likert scale was administered to subjects after each submaximal

155 condition (i.e., 25%, 50 %, and 75% MVIC). It assesses the subjective matching between the

156 intended force and the actual force. In detail, the single-item scale (i.e., "How confident are you in

157 having correctly adhered to the required force?") ranged from 1 (*not confident at all*) to 7

158 (*absolutely confident*).

159 **Data analysis**

160 For the MVIC trials, the highest lower-limb peak force in both TON and BAL conditions was

161 considered among the three trials and expressed as a percentage of body mass (BM%). In the BAL

162 contraction, the three peak values referred to each intended force condition were averaged. In the

163 TON contractions the force signal was averaged within a 200 ms time window starting from the

164 trigger input. The actual force was always normalized to the BM and expressed as a percentage of

165 the MVIC. The accuracy (AC) was calculated as the difference in percentage between the intended

166 and the actual force. In detail, the lower AC values, the higher the accuracy, with a 0 score

167 indicating optimal accuracy. The sum of the Likert scores of the three trials for each intensity (i.e.,

168 25%, 50%, and 75% of the MVIC) was considered for the statistical analysis.

169 **Statistical analysis**

170 A priori power analysis calculation (G*Power 3.1.9.2 software) showed that a total sample size of

171 36 participants and a medium effect size of 0.25 would provide a power of 0.8 with an alpha error

172 probability of 0.01. The mean value and standard deviation (SD) among the three trials for both

173 TON and BAL conditions were calculated for the MVIC, the submaximal intensity (i.e., 25%,

174 50%, and 75% MVIC), and the AC. The Shapiro-Wilk test was used to check the data normality

175 distribution of MET and MVIC (%BM) values. Then, an unpaired sample t-test was used for

176 baseline comparisons between groups (SED vs. ATL). For the AC and Likert scores, a three-way

177 mixed-model analysis of variance (ANOVA) was used to investigate the significant main effect of

178    force intensities (25%, 50%, and 75%), groups (SED vs. ATL), and contractions (TON vs. BAL),

179    and their interactions. Mauchly's test was used to assess the statistical assumption of Sphericity.

180    If Mauchly's Test yields a p-value less than .05, the Greenhouse-Geisser correction was used. The

181    significance level was set at p < 0.05. JASP Software, version 0.16.3.0, was used for statistical

182    analysis.

183    **Results**

184    All the subjects completed the study. Unpaired t-test for baseline comparisons showed statistically

185    significant differences between SED and ATL groups for MET (min/week) and MVIC (%BM) in

186    both BAL and TON contractions (**Table 1**).

187    The results for the strength test (%BM) for the 25%, 50%, and 75% MVIC in both BAL and TON

188    contractions are presented in **Table 2**.

189    The AC results are presented in **Figure 2**. The three-way ANOVA analysis showed a significant

190    main effect of contractions (p < 0.001; F = 19.74; $\eta_p^2$ = 0.34), force intensities (p < 0.001; F =

191    63.09; $\eta_p^2$ = 0.62), and an interaction between them (p < 0.001; F = 14.27; $\eta_p^2$ = 0.27). Moreover,

192    a significant main effect of the group (p < 0.05; F = 4.73; $\eta_p^2$ = 0.11) was observed. In detail, the

193    Bonferroni-Holm post hoc comparisons, shown in **Figure 2**, highlighted the differences among

194    strength tests and between groups. The ATL group showed lower values than the SED group.

195    Following, between-group differences expressed in percentage for (i) BAL contraction (25%

196    MVIC: −3.79%, 50% MVIC: −36.67%, and 75% MVIC: −9.60%) and (ii) TON contraction (25%

197    MVIC: −27.98%, 50% MVIC: −30.36%, and 75% MVIC: −26.76%).

198    The results for the Likert scores in the 25%, 50%, and 75% MVIC in both BAL and TON

199    contractions are presented in **Figure 3**. The three-way ANOVA analysis showed a significant main

200    effect of contractions (p < 0.001; F = 48.85; $\eta_p^2$ = 0.56), and a significant interaction between force

201   intensities and groups ($p < 0.05$; F = 3.49; $\eta_p^2 = 0.08$). In detail, the Bonferroni-Holm post hoc

202   comparisons are shown in **Figure 3**.

203   **Discussion**

204   The purpose of this study was to investigate the relationship between intended and actual force

205   comparing athletes and sedentary individuals during BAL and TON contractions. The main finding

206   confirmed our hypothesis, showing that the ATL group could exert force at the required MVIC

207   percentage more accurately than the SED group, independently of the type of contraction. Since

208   the recruitment and firing rate of the motor units and the contraction type could affect both force

209   production (Enoka & Fuglevand, 2001) and the relationship between intended and actual force

210   (Miyamoto, Kizuka & Ono, 2020), we can assume that sports practice could enhance muscle

211   recruitment strategies (Enoka & Fuglevand, 2001) and the ability to modulate force.

212   Similarly, the higher levels of physical activity and training of ATL account for the higher MVIC

213   values. Therefore, the baseline results supported the hypothesis that the subjects' sports practice

214   could be an influencing variable in force production and claimed for group division when

215   investigating the relationship between intended and actual force. For what concerns the force

216   values recorded in the present study, it is interesting to note that, under all conditions and

217   independently from the group, the actual force tended to overestimate the intended force (**table 2**).

218   Indeed, this underproduction of force was in line with previous results performed on isometric

219   knee extension (Cooper et al., 1979), isokinetic knee extension (Jackson et al., 2006), isometric

220   elbow flexion and extension (John, Liu & Gregory, 2009), and isometric thumb adduction (Cooper

221   et al., 1979). Although the causes of errors in estimation of muscular effort are not completely

222   understood, some possible explanations have been addressed. For instance, a first theory suggests

223   that during voluntary motor task performance, descending motor command signals include

224 physiological noise derived from neuronal and synaptic action potential discharges, which leads

225 to variability in muscle force production (Harris & Wolpert, 1998). In detail, neuronal noise

226 increases with the magnitude of the motor command (i.e., the intensity of a motor task), (John, Liu

227 & Gregory, 2009). A second theory hypothesizes that transient post-contractile potentiation of

228 spinal reflex pathways may summate with previously set motor commands, producing errors in

229 effort perception (Hutton, Enoka & Suzuki, 1984).

230 Even though the actual force globally undershot the intended force, the deviation from the actual

231 force was less marked in the ATL than in the SED group. It is generally accepted that modulation

232 of force is accomplished by a combination of rate coding of individual motor units and recruitment

233 of more or fewer motor units (Clamann, 1993). Moreover, muscle adaptations (e.g., following

234 training) at both neural and morphological levels concur to underpin the enhanced ability of force

235 regulation in skeletal muscle (Folland & Williams, 2007; Carroll et al., 2009). Thus, chronic

236 exposure to training and exercises with repetitive movements against loads for a long time, as

237 competitive athletes regularly do, could have substantially increased their ability to modulate force

238 (Maden-Wilkinson et al., 2020).

239 A better accuracy, in both SED and ATL groups, was observed at lower (i.e., 25% MVIC) rather

240 than higher (50% and 75% MVIC) force intensities. Previous results showed that the presence of

241 an anchoring process (i.e., MVIC as reference), as in our study, seemed to address results in

242 different directions (West et al., 2005). Indeed, West and colleagues reported that when the

243 experimental task was performed prior to the MVIC, the actual force matched the intended force

244 at the intermediate level (i.e., 50% MVIC), while the most accurate match occurred at 25% MVIC

245 without the anchoring process. In contrast with our results, other studies on precision grip (Kumar,

246 Narayan & Chouinard, 1997), power grip (Kumar, Narayan & Chouinard, 1997), chest press

247  (Jackson & Dishman, 2000), and brachial biceps and triceps isometric contractions showed that

248  the actual force matched the intended force at intermediate level (i.e., 40-50% MVC).

249  In our study, the intended force and the actual force output were less associated at higher intensities

250  (50% and 75% MVIC), and thus, the intended force resulted in a more marked perceptual

251  overestimation in these conditions. Hence, our results suggested that a perceptual mistake occurred

252  at higher force intensities even with previous knowledge of the maximal effort (i.e., the MVIC

253  test) as an anchoring process. Even though our data cannot explain why subjects produced the

254  most accurate match at the lower force intensity (25% MVIC), two possible speculations may be

255  acknowledged. First, West and colleagues explained that subjects subconsciously under-produced

256  force at higher intensities as a protective mechanism (West et al., 2005). Indeed, the perceptual

257  overestimation occurred to maintain a reserve capacity and prevent mechanical and metabolic

258  damages, which may occur in further force generation. Second, lower force percentages are used

259  in everyday contexts, most for simple motor tasks (e.g., walking or getting up from a chair).

260  Therefore, subjects could have performed a better perceptual estimation because of the proximity

261  to the levels of force they are accustomed to, regardless of the group.

262  Our findings highlighted that the relationship between intended and actual force was more accurate

263  in the BAL than in the TON condition. Since the BAL contraction occurred rapidly and without

264  afferent sensory feedbacks (Vincken, Gielen & van der Gon, 1984), it was mostly controlled by

265  central predetermined regulatory mechanisms through a feedforward strategy (Hanneton et al.,

266  1997). Conversely, TON contraction had a longer duration, and during this time, information from

267  sensory receptors could interfere with the ongoing task (Desmurget & Grafton, 2000). Indeed,

268  feedback control mechanisms are predominant during the skill acquisition process and essential

269  for constructing a newly learned movement (Seidler, Noll & Thiers, 2004). In our case, the

270   isometric contraction at leg extension represented a basic motor behavior, where corrective

271   feedbacks used in complex motor skills were mostly unnecessary. About that, Lohse and

272   colleagues (Lohse, Sherwood & Healy, 2011) found that an internal focus of attention (i.e.,

273   focusing on muscle contraction) decreased accuracy in a basic motor behavior (i.e., 30% MVIC)

274   compared to an external focus of attention (i.e., focusing on pushing over the force platform).

275   Similarly, subjects in the longer TON contraction could have internally directed their attention on

276   muscles, calling into play counterproductive corrective feedback. This hypothesis could account

277   for the worse accuracy in the TON than BAL contraction, where feedforward mechanisms revealed

278   to be more effective.

279   Finally, subjects' self-perception, deepened through the Likert scale rating at the end of each

280   contraction, highlighted no differences between groups. This result was unexpected, since the ATL

281   group was more accurate in force production, letting suppose a greater awareness in force

282   modulation. However, the motor task studied in this research was a simple one. Thus, we can

283   speculate that a more sport-oriented task could have differentiated the self-confidence performance

284   between athletes and sedentary individuals. Moreover, a main effect of the contraction type was

285   observed in the Likert aggregate scores, with a greater self-confidence towards the TON against

286   the BAL contraction. Since the BAL contraction was the most accurate, we can speculate that the

287   longer time the subjects had to modulate the force led to a perceptual mistake in their self-perceived

288   accuracy in the TON condition.

289   The present study has some potential limitations to be acknowledged. Although the group included

290   athletes and sedentary individuals, the ATL group contained athletes from different sports

291   disciplines. Recruiting athletes from similar sports disciplines with the predominant use of lower

292   limbs could have enhanced the differences with sedentary peers. Moreover, a dynamic or sport-

293    oriented task could have enhanced the accuracy and the self-confidence, being closer to the sport

294    disciplines practiced.

295

296    **Conclusions**

297    The present study expanded the previous results on the relationship between the intended and the

298    actual force by investigating whether sports practice could be an influencing factor. Since, the

299    accuracy between intended and actual forces seems to decrease as a function of the increment of

300    the force intensity, our results suggested to coaches and practitioners to focus on training the force

301    accuracy at high intensity. Sports situations require of fast movements, and in most situations, high

302    level of strength thus the accuracy is supposed to be an important factor to achieve prominent

303    performance. Indeed, repetitive training may improve the accuracy of force production also at high

304    force levels. Differences in accuracy between ballistic and tonic contraction suggest different

305    control mechanisms. Further work is needed to explore these hypotheses as well to deepen the

306    perceptual overestimation detected at the higher isometric force intensities.

307    **Acknowledgments**

308    The authors would like to thank all the subjects who voluntarily participated in the study.

309

310    **Competing interests**

311    The authors declare no competing interests.

312    **Funding**

313    This research did not receive any specific grant from funding agencies in the public, commercial,

314    or not-for-profit sectors.

315  **References**

316

317  Baweja HS, Patel BK, Martinkewiz JD, Vu J, Christou EA. 2009. Removal of visual feedback

318      alters muscle activity and reduces force variability during constant isometric contractions.

319      *Experimental brain research* 197:35–47. DOI: 10.1007/S00221-009-1883-5.

320  Bhanpuri NH, Okamura AM, Bastian AJ. 2012. Active force perception depends on cerebellar

321      function. *Journal of neurophysiology* 107:1612–1620. DOI: 10.1152/JN.00983.2011.

322  Bull FC, Maslin TS, Armstrong T. 2009. Global Physical Activity Questionnaire (GPAQ): Nine

323      Country Reliability and Validity Study. *Journal of Physical Activity and Health* 6:790–804.

324      DOI: 10.1123/JPAH.6.6.790.

325  Carroll TJ, Barton J, Hsu M, Lee M. 2009. The effect of strength training on the force of

326      twitches evoked by corticospinal stimulation in humans. *Acta Physiologica* 197:161–173.

327      DOI: 10.1111/J.1748-1716.2009.01992.X.

328  Carson RG, Riek S, Shahbazpour N. 2002. Central and peripheral mediation of human force

329      sensation following eccentric or concentric contractions. *The Journal of Physiology*

330      539:913–925. DOI: 10.1113/JPHYSIOL.2001.013385.

331  Clamann HP. 1993. Motor Unit Recruitment and the Gradation of Muscle Force. *Physical*

332      *Therapy* 73:830–843. DOI: 10.1093/PTJ/73.12.830.

333  Cooper DF, Grimby G, Jones DA, Edwards RHT. 1979. Perception of effort in isometric and

334      dynamic muscular contraction. *European Journal of Applied Physiology and Occupational*

335      *Physiology* 41:173–180. DOI: 10.1007/BF00430009/METRICS.

336    Cortis C, Tessitore A, Perroni F, Lupo C, Pesce C, Ammendolia A, Capranica L. 2009. Interlimb

337        coordination, strength, and power in soccer players across the lifespan. *Journal of strength*

338        *and conditioning research* 23:2458–2466. DOI: 10.1519/JSC.0B013E3181BC1B39.

339    Desmurget M, Grafton S. 2000. Forward modeling allows feedback control for fast reaching

340        movements. *Trends in cognitive sciences* 4:423–431. DOI: 10.1016/S1364-6613(00)01537-

341        0.

342    Enoka RM, Fuglevand AJ. 2001. Motor unit physiology: Some unresolved issues. *Muscle and*

343        *Nerve* 24:4–17. DOI: 10.1002/1097-4598(200101)24:1<4::AID-MUS13>3.0.CO;2-F.

344    Folland JP, Williams AG. 2007. The adaptations to strength training: Morphological and

345        neurological contributions to increased strength. *Sports Medicine* 37:145–168. DOI:

346        10.2165/00007256-200737020-00004/FIGURES/7.

347    Hagberg JM, Seals DR, Yerg JE, Gavin J, Gingerich R, Premachandra B, Holloszy JO. 1988.

348        Metabolic responses to exercise in young and older athletes and sedentary men. *Journal of*

349        *applied physiology (Bethesda, Md. : 1985)* 65:900–908. DOI:

350        10.1152/JAPPL.1988.65.2.900.

351    Hanneton S, Berthoz A, Droulez J, Slotine JJE. 1997. Does the brain use sliding variables for the

352        control of movements? *Biological cybernetics* 77:381–393. DOI: 10.1007/S004220050398.

353    Harris CM, Wolpert DM. 1998. Signal-dependent noise determines motor planning. *Nature 1998*

354        *394:6695* 394:780–784. DOI: 10.1038/29528.

355    Hutton RS, Enoka RM, Suzuki S. 1984. Activation history and constant errors in human force

356        production. *Brain Research* 307:344–346. DOI: 10.1016/0006-8993(84)90491-8.

357 Jackson AW, Dishman RK. 2000. Perceived submaximal force production in young adult males

358 and females. *Medicine and science in sports and exercise* 32:448–451. DOI:

359 10.1097/00005768-200002000-00028.

360 Jackson AW, Ludtke AW, Martin SB, Koziris LP, Dishman RK. 2006. Perceived submaximal

361 force production in young adults. *Research Quarterly for Exercise and Sport* 77:50–57.

362 DOI: 10.1080/02701367.2006.10599331.

363 John EB, Liu W, Gregory RW. 2009. Biomechanics of muscular effort: age-related changes.

364 *Medicine and science in sports and exercise* 41:418–425. DOI:

365 10.1249/MSS.0B013E3181884480.

366 Jones LA, Hunter IW. 1982. Force sensation in isometric contractions: a relative force effect.

367 *Brain research* 244:186–189. DOI: 10.1016/0006-8993(82)90919-2.

368 Jones LA, Hunter IW. 1983. Effect of fatigue on force sensation. *Experimental neurology*

369 81:640–650. DOI: 10.1016/0014-4886(83)90332-1.

370 Kumar S, Narayan Y, Chouinard K. 1997. Effort reproduction accuracy in pinching, gripping,

371 and lifting among industrial males. *International Journal of Industrial Ergonomics* 20:109–

372 119. DOI: 10.1016/S0169-8141(96)00045-5.

373 Lohse KR, Sherwood DE, Healy AF. 2011. Neuromuscular Effects of Shifting the Focus of

374 Attention in a Simple Force Production Task.

375 *http://dx.doi.org/10.1080/00222895.2011.555436* 43:173–184. DOI:

376 10.1080/00222895.2011.555436.

377 Maden-Wilkinson TM, Balshaw TG, Massey GJ, Folland JP. 2020. What makes long-term

378     resistance-trained individuals so strong? A comparison of skeletal muscle morphology,

379     architecture, and joint mechanics. *Journal of Applied Physiology* 128:1000–1011. DOI:

380     10.1152/JAPPLPHYSIOL.00224.2019.

381 van Melick N, Meddeler BM, Hoogeboom TJ, Nijhuis-van der Sanden MWG, van Cingel REH.

382     2017. How to determine leg dominance: The agreement between self-reported and observed

383     performance in healthy adults. *PLOS ONE* 12:e0189876. DOI:

384     10.1371/JOURNAL.PONE.0189876.

385 Miyamoto T, Kizuka T, Ono S. 2019. The Influence of Contraction Types on the Relationship

386     Between the Intended Force and the Actual Force.

387     *https://doi.org/10.1080/00222895.2019.1680947* 52:687–693. DOI:

388     10.1080/00222895.2019.1680947.

389 Miyamoto T, Kizuka T, Ono S. 2020. The Influence of Contraction Types on the Relationship

390     Between the Intended Force and the Actual Force. *Journal of motor behavior* 52:687–693.

391     DOI: 10.1080/00222895.2019.1680947.

392 Pageaux B. 2016. Perception of effort in Exercise Science: Definition, measurement and

393     perspectives. *European journal of sport science* 16:885–894. DOI:

394     10.1080/17461391.2016.1188992.

395 Proske U, Allen T. 2019. The neural basis of the senses of effort, force and heaviness.

396     *Experimental brain research* 237:589–599. DOI: 10.1007/S00221-018-5460-7.

397 Seidler RD, Noll DC, Thiers G. 2004. Feedforward and feedback processes in motor control.

398     *NeuroImage* 22:1775–1783. DOI: 10.1016/J.NEUROIMAGE.2004.05.003.

399   Thorstensson A, Larsson L, Tesch P, Karlsson J. 1977. Muscle strength and fiber composition in

400       athletes and sedentary men. *Medicine and Science in Sports* 9:26–30. DOI:

401       10.1249/00005768-197721000-00004.

402   Vincken MH, Gielen CCAM, van der Gon JJD. 1984. Stiffness control after fast goal-directed

403       arm movements. *Human Movement Science* 3:269–280. DOI: 10.1016/0167-

404       9457(84)90021-6.

405   West SJ, Smith L, Lambert E V., Noakes TD, Gibson ASC. 2005. Submaximal force production

406       during perceptually guided isometric exercise. *European Journal of Applied Physiology*

407       95:537–542. DOI: 10.1007/S00421-005-0004-9/TABLES/3.

408

409   **Figure legends**

410   **Figure 1. Graphical representation of the experimental design.** Custom-built chair

411   instrumented with a uni-axial load cell (A); ballistic isometric condition with a representative force

412   graph (B); tonic isometric condition with a representative graph of the force. The trigger input

413   marked the beginning of the matching between intended and actual forces, according to the

414   subject's perception (C).

415   **Figure 2. Isometric strength results.** Accuracy (AC) in athletes (ATL) and sedentary (SED)

416   individuals during ballistic and tonic contraction at the different force intensities (25%, 50%, and

417   75% MVIC). Data are presented as mean ± standard deviation. # (p < 0.001); *** (p < 0.001).

418   **Figure 3. Results of the perceived accuracy.** Likert Scores between actual and intended force in

419   athletes (ATL) and sedentary (SED) individuals during ballistic and tonic contraction at different

420 force intensities (25%, 50%, and 75% MVIC). Data are presented as mean ± standard deviation.

421 *** (p < 0.001).

422

423

424

425

426

427 **Tables legends**

428 **Table 1. Baseline comparisons.** MVIC: maximal voluntary isometric contraction; BAL: ballistic

429 contraction; TON: tonic contraction; SED: sedentary; ATL: athletes; BM: Body Mass. MET:

430 Metabolic Equivalent. Data are presented as mean ± standard deviation (SD).

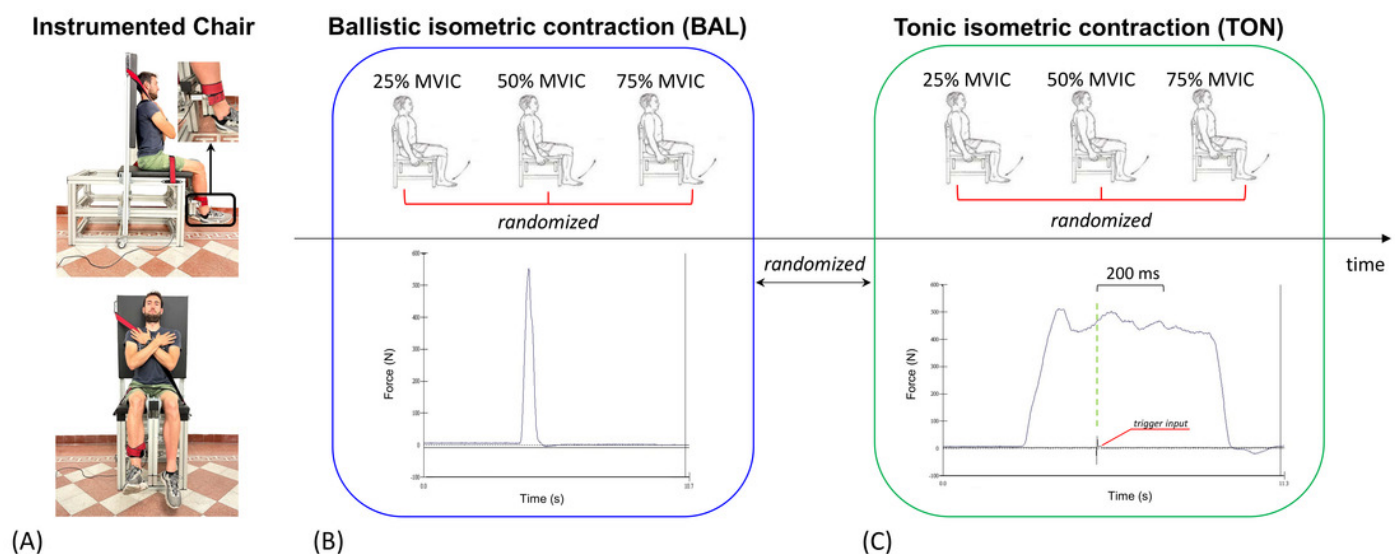
431 **Table 2. Results of the actual force for all the intended force conditions (i.e., 25%, 50%, and**

432 **75% MVIC)**. MVIC: maximal voluntary isometric contraction; BAL: ballistic contraction; TON:

433 tonic contraction; SED: sedentary; ATL: athletes. Data are presented as mean ± standard deviation.

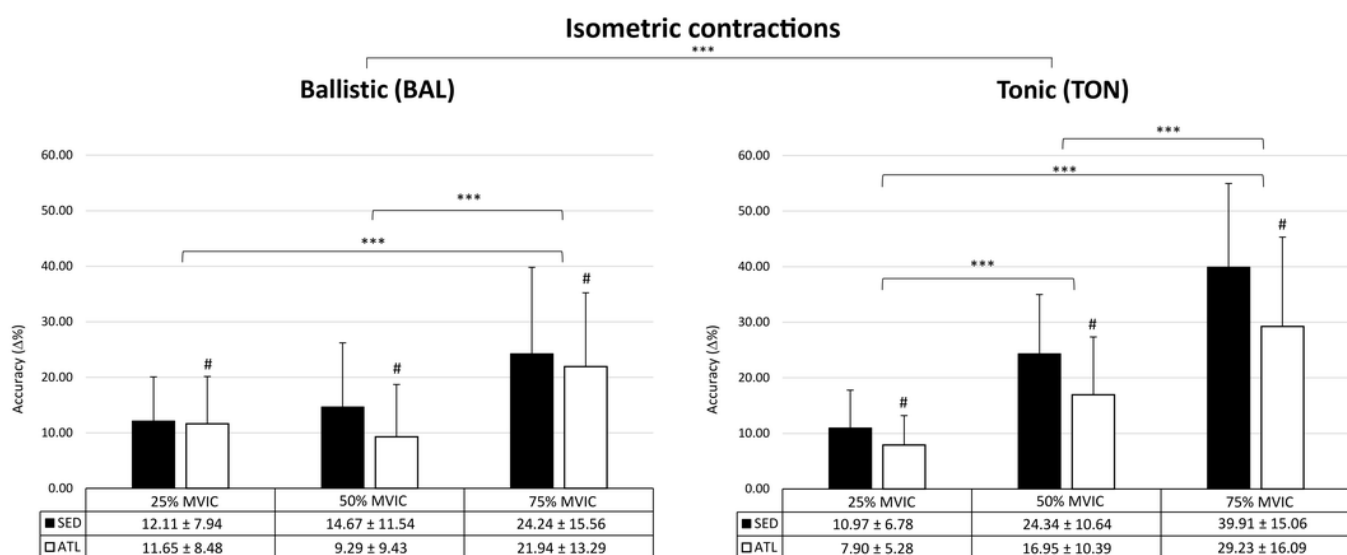
# Figure 1

Graphical representation of the experimental design.

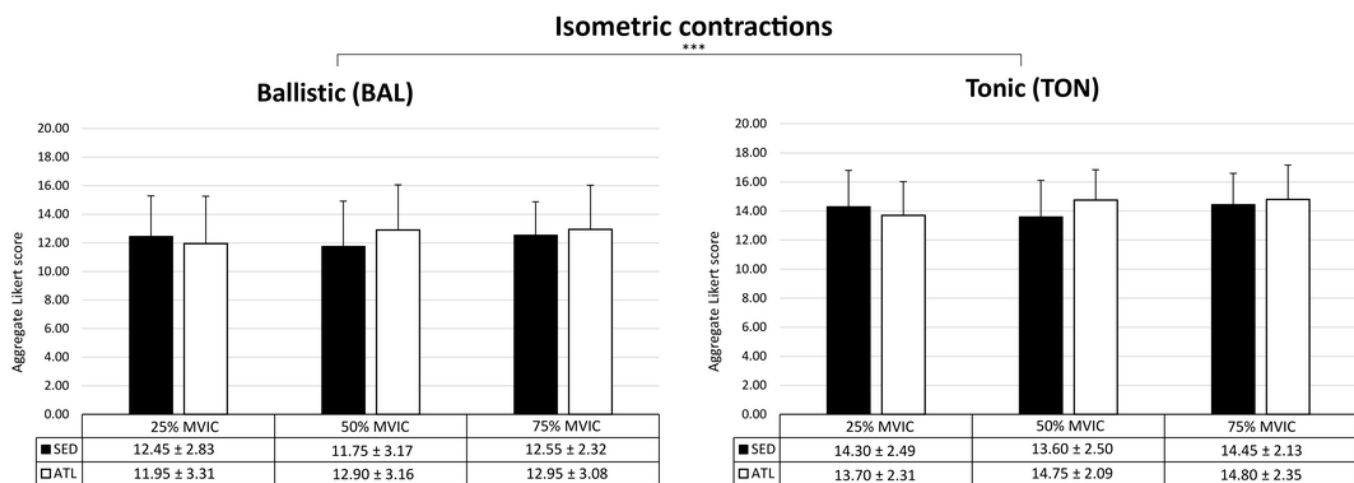
Custom-built chair instrumented with a uni-axial load cell (A); ballistic isometric condition with a representative force graph (B); tonic isometric condition with a representative graph of the force. The trigger input marked the beginning of the matching between intended and actual forces, according to the subject's perception (C).

(A)   (B)   (C)

# Figure 2

Isometric strength results.

Accuracy (AC) in athletes (ATL) and sedentary (SED) individuals during ballistic and tonic contraction at the different force intensities (25%, 50%, and 75% MVIC). Data are presented as mean ± standard deviation. # (p < 0.001); *** (p < 0.001).

# Figure 3

Results of the perceived accuracy.

Likert Scores between actual and intended force in athletes (ATL) and sedentary (SED) individuals during ballistic and tonic contraction at different force intensities (25%, 50%, and 75% MVIC). Data are presented as mean ± standard deviation. *** (p < 0.001).

Baseline comparisons.

MVIC: maximal voluntary isometric contraction; BAL: ballistic contraction; TON: tonic contraction; SED: sedentary; ATL: athletes; BM: Body Mass. MET: Metabolic Equivalent. Data are presented as mean ± standard deviation (SD).

1 **Table 1. Baseline comparisons.**

|  | **SED Group** | **ATL Group** | **p value** |
|---|---|---|---|
| **MET** (min/week) | 1408.00 ± 1333.96 | 7675.20 ± 4480.24 | p < 0.001 |
| **MVIC-BAL** (%BM) | 50.785 ± 25.784 | 77.38 ± 21.45 | p < 0.001 |
| **MVIC-TON** (%BM) | 69.34 ± 23.00 | 105.84 ± 19.48 | p < 0.001 |

5 MVIC: maximal voluntary isometric contraction; BAL: ballistic contraction; TON: tonic
6 contraction; SED: sedentary; ATL: athletes; BM: Body Mass. MET: Metabolic Equivalent.

Results of the actual force for all the intended force conditions (i.e., 25%, 50%, and 75% MVIC).

MVIC: maximal voluntary isometric contraction; BAL: ballistic contraction; TON: tonic contraction; SED: sedentary; ATL: athletes. Data are presented as mean ± standard deviation.

1 **Table 2. Results of the actual force for all the intended force conditions (i.e., 25%, 50%, and**
2 **75% MVIC).**

| | SED Group | | ATL Group | |
|---|---|---|---|---|
| Intended force | BAL (%MVIC) | TON (%MVIC) | BAL (%MVIC) | TON (%MVIC) |
| **25% MVIC** | 30.43 ± 13.65 | 16.05 ± 9.41 | 34.34 ± 11.09 | 23.76 ± 9.60 |
| **50% MVIC** | 44.03 ± 17.96 | 25.96 ± 11.35 | 47.09 ± 13.07 | 36.64 ± 14.92 |
| **75% MVIC** | 53.26 ± 19.12 | 35.08 ± 15.06 | 53.87 ± 14.63 | 46.45 ± 17.34 |

5 MVIC: maximal voluntary isometric contraction; BAL: ballistic contraction; TON: tonic
6 contraction; SED: sedentary; ATL: athletes.