



Effects of peak torque angle on the bilateral deficit of knee extensors and flexors at two velocities of contraction

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Abstract

Purpose To examine effects of the peak torque angle (PTA) on the bilateral deficit (BD) index at two low velocities of contraction.

Methods Twenty young men performed right and left knee concentric extension–flexion (1 set, 5 repetitions) unilaterally and bilaterally in an isokinetic dynamometer at 30°/s and 60°/s. The peak torque (PT) from right, left and bilateral tests and their respective PTA were registered. Two BD indexes were determined as the bilateral PT divided by the summation of right and left PT (BDI_1) and by the summation of left and right torque values found at the bilateral PTA (BDI_2). Additionally, the mean of the absolute differences (MAD) between bilateral and unilateral PTAs was calculated as the mean of the modulus of the difference between bilateral minus right and bilateral minus left values divided.

Results The knee extensors showed difference between bilateral and unilateral PTA ($p < 0.01$) and effect of velocity on bilateral PTA ($p < 0.05$). MAD was not influenced by the direction of movement ($p = 0.673$), whereas on knee flexors it depended on velocity ($p = 0.01$). Knee extensors and flexors presented higher BDI_1 than BDI_2 at both velocities ($p < 0.001$). The difference between BDI_1 and BDI_2 was strongly correlated with MAD ($p < 0.01$).

Conclusion The BD is generally attributed to neural mechanisms, whereas the BD index was influenced by the PTA. Hence, it is suggested that the angle–torque relationship plays a role on the BD reported because it may enhance the BD index.

Keywords Isokinetic contraction · Muscle mechanics · Biomechanics

Introduction

The bilateral deficit (BD) describes the difference in maximal force generating capacity of muscles when they are contracted alone, or together with the contralateral muscle group and the deficit occurs when the summed unilateral forces is greater than the bilateral force [12, 20, 34]. As higher is the difference between the summed and bilateral forces, greater is the BD, which is quantified by the BD index [5]. Among the investigated possible influencing factors on the BD, such as age [10, 21, 25] and gender [10, 29], only physical fitness

status [3, 12, 29] and type of contraction [11, 14, 26, 34] showed to significantly affect the BD [21, 25, 34].

Some theories try to explain the causal mechanisms behind BD, although no consensus is established to date. It has been proposed that this phenomenon may be caused by differences between unilateral and bilateral movement control [11, 14, 29]. In addition, it is suggested that during bilateral exertion spinal reflex are enabled [17, 23] and furthermore it is proposed that an inhibition of the central nervous system at the brain level provokes lower level of cerebral hemispheres activation during bilateral contractions [25, 27, 32]. Such conditions would lead to both activate the antagonist muscles [13, 22, 26] and reduce the amount of motor units recruited by the agonists [20, 33]. Nevertheless, besides neural mechanisms, one could not neglect the influence of muscle mechanical properties and biomechanical issues as, among others, the torque produced by other muscles to body adjustments and stabilization during bilateral vs. unilateral condition [30].

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Some studies have employed maximal isokinetic outcomes as maximal torque or force to investigate effects of velocity of exertion on the BD of knee extensors or flexors [5, 9, 25, 33], aiming to prove that and/or muscle fiber elicit the BD, but conflicting outcomes are reported. Dickin and Too [9] measured isokinetic torque of knee extensors at 60°/s, 90°/s, 120°/s, 150°/s and 180°/s and reported that the BD increased with the velocity. Conversely, Brown et al. [5] reported a reduction of the BD in knee extensors and flexors as the angular velocity increased (60°/s, 120°/s, 180°/s, 240°/s). On the other hand, Owings and Grabiner [25] compared 30°/s to 150°/s and found no difference on the BD of knee extensors. Such conflicting results may potentially be attributed to the fact that isokinetic machine does not account for the limb inertial moment and acceleration. Thus, measuring the peak torque (PT) or force at high velocity notwithstanding the angular position may lead to erroneous conclusions about the maximal capacity of torque generation of the tested muscle group [2, 15]. As high is the velocity, wider is the time window of angular acceleration and, thus, if the joint angle where the PT is found—known as the peak torque angle (PTA) [19, 28]—is within such a window, the actual PT may not be recognized as this tends to occur earlier in the range of movement [2]. Moreover, as the bilateral torque is provided by homologous unilateral muscles acting simultaneously, hence the bilateral PTA could be different from the PTA of the unilateral tests and this difference could lead to misestimating the BD index.

Although studies have employed isokinetic machine to investigate BD, none of them have addressed the effect of PTA on their results. Additionally, PTA has been showed to depend on testing velocity [15] and furthermore there is no information on PTA of knee extensors or flexors during bilateral tasks. Therefore, this study measured the unilateral and bilateral PT and PTA of knee extensors and flexors during isokinetic exertion at two low angular velocities aiming at investigate the effect of PTA on BD index. Additionally, effects of velocity of movement on BD are examined.

Materials and methods

Participants

The sample of this study comprised 20 volunteers males with mean (SD) age 29.1 (5.00) years, height 175.1 (6.10) cm and body mass 81.3 (11.10) kg. All self-reported right leg dominance, which was determined as the participants' preferred kicking leg. The inclusion criteria were: (a) to be regularly recreational resistance training practitioners (2–3 sessions per week); (b) between 20 and 40 years old and (c) right leg dominance. The exclusion criteria were (a) history of knee and/or muscle injuries or (b) any disabling health problem to perform

the tests. The test protocol was previously approved by local Ethics Committee for Human Study (allowance n. 477.583). Before participation in the study, the aims and procedures were explained to the volunteers, who subsequently provided written informed consent.

Test procedures

All torque signals were acquired by the isokinetic dynamometer CSMI HUMAC NORM (USA). Participants were seated barefoot with their trunk reclined at approximately 90° and secured by seat-belts. Regular calibration procedures were completed before each test and the limb weight was measured. Prior to each test, participants accomplished a warm-up familiarization protocol comprising movements of knee extension and flexion unilaterally (right and left) and bilaterally. Each test consisted of one set of five repetitions of concentric–concentric exertion (extension followed by flexion) at the velocities 30°/s and 60°/s. A between-tests recovery period of 10 min was allowed. The bilateral test was carried out by a custom-made apparatus (Fig. 1).

Torque signal processing and variables calculation

The recorded signals of torque and angular position were transferred into a computer, so that all calculation procedures were accomplished by a custom-built routine developed in MatLab 7.02c (MathWorks Inc., USA). The torque signal of each test was first filtered by a second-order low-pass Butterworth filter applied in the forward and reverse directions, allowing zero-phase, with a cutoff frequency of 10 Hz. After that it was measured the PT from the torque signal of each repetition accomplished by each subject. From the five repetitions, the one that presented the highest PT had the torque and angle signals stored. The variables extracted from those signals to be employed in the calculations are illustrated in Fig. 2, which were the PT of right, left and bilateral tests, their corresponding PTA and the values of the right and left torque at the bilateral PTA. All variables were extracted from extensors and flexors signals at each velocity.

The BD index was computed by Eq. 1 (BDI_1), previously described by Brown et al. [5] and Eq. 2 (BDI_2)—proposed in the present study—which takes into account the unilateral torques found at BA:

$$BDI_1 = \frac{BPT \times 100}{RPT + LPT} - 100, \quad (1)$$

where BPT is the bilateral, RPT the right and LPT the left peak torque:

$$BDI_2 = \frac{BPT \times 100}{RTBA + LTBA} - 100, \quad (2)$$

Fig. 1 Illustration of the unilateral (right and left) and bilateral tests, showing the apparatus employed to bilateral accomplishment. The knee angle differences caused by the different positions of the unilateral and bilateral bars at the ankle(s) were included during calibration procedures to be considered within all calculations

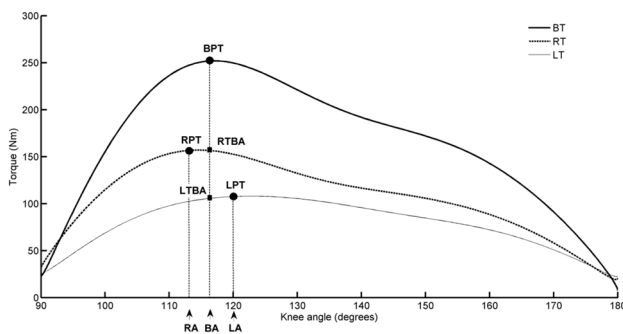
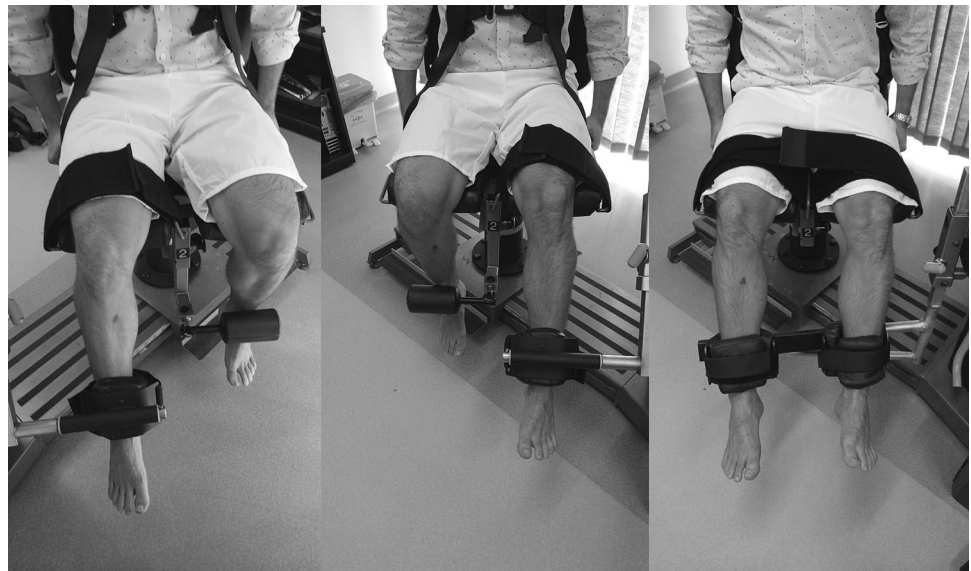


Fig. 2 Signals of bilateral (BT), right (RT) and left (LT) torques from one subject, illustrating the variables obtained, which were the right (RPT=157 Nm), left (LPT=112 Nm) and bilateral (BPT=252 Nm) peak torque, together with their respective peak torque angle (RA right angle; LA left angle; BA bilateral angle) and the torque value measured at the BA from the right (RTBA) and left (LTBA) unilateral torque signals

where BPT is the bilateral PT, RTBA and LTBA are, respectively, the right and left unilateral torque values at the peak torque angle of the bilateral test (see Fig. 2).

Additionally, the relative difference between the two BD indexes was calculated by Eq. 3. Further, the mean absolute difference (MAD) between the PTA of the right and left vs. bilateral test was determined by Eq. 4:

$$\%DI = (|BDI_1 - BDI_2|/BDI_1) \times 100, \quad (3)$$

where %DI is the relative difference between the BD indexes BDI_1 and BDI_2 with respect to BDI_1 :

$$MAD = (|RA - BA| + |LA - BA|)/2, \quad (4)$$

where RA is the right, LA the left and BA the bilateral peak torque angle.

Statistical procedures

The Shapiro–Wilk test was applied to the variables investigated, which showed to be normally distributed ($p > 0.05$). The effect of velocity on right, left and bilateral PT and their corresponding PTA was investigated by paired t test applied to the knee extensors and flexors. In addition, the effect size (ES) was also calculated as Cohen's d , by Eq. 5. The PTA from bilateral and from right and left unilateral tests were compared by 1-way repeated measures ANOVA applied to extensors and flexors at both velocities. The interaction between velocity and BD indexes (BDI_1 and BDI_2) was tested by 2-way repeated measures ANOVA applied to extensors and flexors. The influence of velocity and movement direction (extension and flexion) on MAD and %DI was tested by 2-way repeated measures ANOVA. All repeated measures ANOVA were previously tested for sphericity and if this could not be assumed the Greenhouse–Geisser correction for degree of freedom was employed. Further, post hoc of Bonferroni for pairwise comparison was achieved when necessary. The association between MAD and %DI was tested by Pearson correlation coefficient. All calculations were carried out in IBM SPSS for windows (USA) and the graphics were produced in Graphpad Prism (USA). The significance level was set at 0.05:

$$d = (\bar{X}_{60} - \bar{X}_{30})/S_{30}, \quad (5)$$

where d is the Cohen's d (ES), $\bar{X}_{60}$ is the mean of the variable measured at $60^\circ/s$, $\bar{X}_{30}$ at $30^\circ/s$ and S_{30} is the standard deviation of the variable measured at $30^\circ/s$.

Table 1 Mean (SD) peak torque (Nm) of bilateral (BPT), right (RPT) and left (LPT), together with the mean (SD) peak torque angle (°) of bilateral (BA), and right (RA) and left (LA) unilateral tests

	Extensor				Flexor			
	30°/s	60°/s	<i>p</i>	ES	30°/s	60°/s	<i>p</i>	ES
BPT	325 (88.3)	313 (71.9)	0.301	−0.14	239 (49.4)	230 (37.8)	0.237	−0.18
RPT	225 (75.3)	200 (53.1)	0.011	−0.33	159 (50.3)	146 (27.4)	0.166	−0.26
LPT	207 (65.4)	197 (46.0)	0.160	−0.15	150 (29.0)	140 (25.0)	0.039	−0.34
BA	126 (9.9)	133 (11.1)	<0.001	0.71	147 (10.4)	145 (6.6)	0.238	−0.19
RA	122 (7.9)	126 (8.1)	0.021	0.51	150 (9.3)	146 (6.8)	0.145	−0.43
LA	122 (9.4)	128 (8.2)	0.009	0.64	151 (6.8)	147 (4.2)	0.036	−0.59

The data are from knee extensors and flexors at the two velocities. The *p* values and effect size (ES) regard to comparisons between velocities. Significant *p* values are highlighted

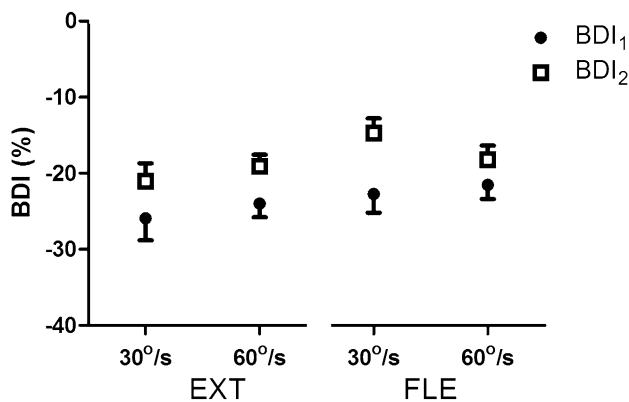


Fig. 3 Mean and 95% confidence interval of bilateral deficit indexes (BDI) calculated without (BDI₁) and with (BDI₂) accounting for the effect of peak torque angle of the bilateral test, for both speeds, knee extensor (EXT) and flexors (FLE). BDI₁ presented significantly higher absolute values than BDI₂ on extensors and flexors at both speeds

Results

From the unilateral tests, only right knee extensors and left knee flexors presented significantly higher PT at 30°/s than at 60°/s, whereas no effect of the velocity was found on extensors and flexors of the bilateral test (Table 1). The bilateral test showed the PTA of knee extensors to be significantly higher at 60°/s than 30°/s, but no effect of the velocity was found on knee flexors (Table 1). The PTA of knee extensors from the bilateral test was significantly different of the right and left unilateral tests at 30°/s ($p=0.005$) and at 60°/s ($p<0.008$), but the PTA of knee flexors showed no significant difference among the three tests ($p=0.3231$).

One subject did not show BD on knee extensors and flexors at both velocities, i.e., presented positive values of BDI₁. One more subject presented positive values of BDI₂ on knee flexors at both velocities. BDI₁ showed significantly higher absolute value than BDI₂ ($p<0.001$), at both velocities and both directions (Fig. 3). No interaction was found between the BD indexes (BDI₁ and BDI₂) and velocity ($p=0.590$) for knee extensors and flexors. The %DI (Fig. 4) was not affected by velocity (0.672) or direction of movement (0.057) and, among all tests and participants, %DI reached values as high

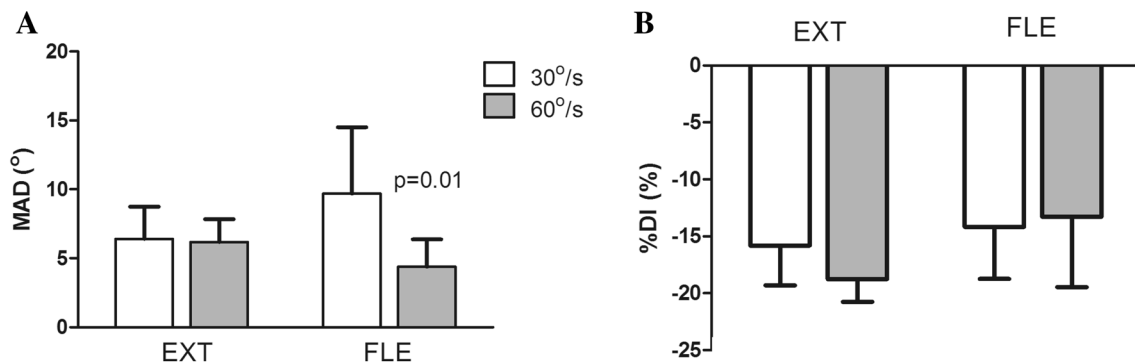


Fig. 4 Mean and 95% confidence interval of **a** mean of absolute difference (MAD) between bilateral PTA and left PTA and between BA and right PTA, determined by Eq. 4 and **b** difference between BDI₁

and BDI₂ expressed as percentage of BDI₁ (%DI) obtained from knee extensors (EXT) and flexors (FLE) at both speeds

as 57%. The MAD value (Fig. 4) was not affected by muscle group ($p=0.673$) and only MAD of flexors was influenced by the velocity ($p=0.012$).

The test of correlation between %DI and MAD resulted in the following results: from knee extensors at 30°/s, $r=-0.64$ ($p=0.009$) and at 60°/s, $r=-0.85$ ($p<0.001$); from knee flexors at 30°/s, $r=-0.64$ ($p=0.007$) and at 60°/s, $r=-0.93$ ($p<0.001$).

Discussion

The measurement of isokinetic PT has been widely employed to assess muscular strength [11, 26, 31] and investigations on BD have also been carried out by this method [20, 26], including studies aiming at examine the effect of testing velocity on the BD [5, 9, 25, 33]. Besides the isokinetic PT, the present study assessed the PTA of unilateral and bilateral tests in order to investigate if part of the BD could be elicited by the angle $\times$ torque (muscle length $\times$ tension) relationship. Furthermore, the investigation included two velocities as PTA from unilateral tests has been showed to be velocity dependent [15]. The two velocities elected were low in order to avoid the influence of initial acceleration in the PTA, since high velocities lead to produce earlier PT within the range of movement [2].

The PTA of unilateral tests showed the average values to be in accordance with previous reports for knee extensors [1, 6, 8, 18] and flexors [4, 6, 7]. In terms of effect of velocity, the knee extensors showed the PT to occur latter at 60°/s when compared to 30°/s, whereas knee flexors presented a contrasting trend. Kannus and Beynon [15] reported PTA as being affected by angular velocity of knee extensors and flexors, but they compared velocities with greater difference (60°/s against 180°/s). Thus, the results of the present work appears to be surprising and further indicates that despite the choice of two low velocities to avoid effect of acceleration on the PTA, even being small, the difference between the velocities elicited effect on such an angle. Concerning the bilateral test, there is no information in the literature about PTA, whereas in the present study this occurred earlier at 30°/s than 60°/s on knee extensors. In addition, at both velocities, it was found higher bilateral than unilateral PTA on knee extensors.

The present study showed no effect of velocity and direction of movement on the BD when measured by BDI_1 , the usual method employed to calculate the BD index [5] and BDI_2 , while studies on effect of velocity on the BD show conflicting results. In this context, the results of such effects have been employed to propose neural mechanisms and/or muscle fiber types as eliciting the BD. Brown et al. [5] investigated the BD of knee extensors

and flexors at 60°/s, 120°/s, 180°/s, 240°/s and 330°/s, and observed a decrease of BD index as the velocity increased. The authors [5] attributed this behavior to the reduction of activation of slow-twitch fibers. Conversely, Vandervoort et al. [33] evaluated the BD during leg press exercise and reported that the BD index increased together with velocity. Similarly, Dickin and Too [9] reported higher BD index of knee extensors at higher velocities when comparing 30°/s, 60°/s, 90°/s, 120°/s, 150°/s and 180°/s. In both studies [9, 33], the BD was attributed to less activation of fast-twitch fibers. On the other hand, Owings and Grabiner [25] found no BD index difference from knee extensors when comparing 30°/s against 150°/s, whereas after inducing muscular fatigue the index increased at the velocity 30°/s. To the authors [25], their findings do not support the theory that the BD is caused by depressed activation of fast-twitch fibers. Vandervoort et al. [34] applied a similar protocol employed previously [33], but for upper limbs no effect of velocity on BD was observed. According to Vandervoort et al. [34], the disagreeing results obtained between their study and that conducted by Vandervoort et al. [33] may have grounds on different patterns of muscular activation of arms and legs.

The hypotheses proposed to explain the mechanisms behind the BD do not seem to be fully elucidative. Most investigators have suggested that the BD is associated to neural issues such as neural inhibition of agonist [14, 16, 17, 23, 24, 33], increased activation of antagonist [13, 20, 22, 26] and lower activation of type II muscle fibers [14, 16, 20, 23, 33]. Nonetheless, the influence of biomechanical variables on the BD appears to be ignored, while non-harmonious mechanical behavior of right and left limb acting simultaneously may modify the production of maximal muscle force or torque exerted bilaterally. One of such situations approached by the present study was the PTA. As joint angle depends on muscle length, which determines the muscle capacity of force production, we hypothesized that part of the BD could be explained by the different PTAs from the bilateral and unilateral tests. The results showed that BDI_2 (which took into account the PTA) had significantly absolute lower value than BDI_1 . Additionally, the relative difference between BDI_1 and BDI_2 (%DI) reached 57%, which means that while considering the PTA in the calculation of the BD index, this could be much lower. Furthermore, good correlation values were found between %DI and the absolute mean difference between unilateral and bilateral PTA, at both velocities and muscle groups. These results strongly indicate that angle–torque relationship may highlight the BD indexes reported in the literature. These findings also provide insights that effects of biomechanical variables on the BD should be further investigated.

Conclusion

This study showed that the BD of knee extensors and flexors at 30°/s did not significantly differ from that at 60°/s, whereas the PTA of knee extensors was significantly influenced by the testing velocity in all tests. Lower values of BD indexes were found when taking into account the PTA in their calculation. Furthermore, good correlations were found between the difference of the two BD indexes and the mean absolute difference between bilateral and unilateral PTA. Hence, while the BD phenomenon is not completely understood, albeit it is proposed that neural and fiber type issues elicit the BD, the results of this study suggest that the angle–torque relationship plays an important role on the BD reported because it may potentially enhance the BD index. These results give grounds to future investigation of effects of biomechanical variables on the BD.

Compliance with ethical standards

Conflict of interest The authors declare that there are no conflicts of interest regarding the data presented in the paper.

Ethical approval The whole protocol was approved by the ethical committee of the Instituto Nacional de Traumatologia e Ortopedia for experiments with humans (allowance n. 477.583), in accordance with the national committee and with the 1964 Helsinki declaration and the latter amendments or comparable ethical standards.

Informed consent All volunteers who participated in the study were instructed about the procedures and gave a signed written consent.

References

- Akima H, Saito A (2013) Inverse activation between the deeper vastus intermedius and superficial muscles in the quadriceps during dynamic knee extensions. *Muscle Nerve* 47(5):682–690. <https://doi.org/10.1002/mus.23647>
- Baltzopoulos V, Brodie DA (1989) Isokinetic dynamometry: applications and limitation. *Sports Med* 8(2):101–116
- Botton CE, Radaelli R, Wilhelm EN, Silva BGC, Brown LE, Pinto RS (2013) Bilateral deficit between concentric and isometric muscle actions. *Isokinet Exerc Sci* 21:161–165. <https://doi.org/10.3233/IES-130492>
- Brockett CL, Morgan DL, Proske U (2004) Predicting hamstring strain injury in elite athletes. *Med Sci Sports Exerc* 36(3):87–379. <https://doi.org/10.1249/01.MSS.0000117165.75832.05>
- Brown LE, Whitehurst M, Gilbert R, Findley BW, Buchalter DN (1994) Effects of velocity on the bilateral deficit during dynamic knee extension and flexion exercises in females. *Isokinet Exerc Sci* 4(4):153–156. <https://doi.org/10.3233/IES-1994-4406>
- Brughelli M, Mendiguchia J, Nosaka K, Idoate F, Arcos AL, Cronin J (2010) Effects of eccentric exercise on optimum length of the knee flexors and extensors during the preseason in professional soccer players. *Phys Ther Sport* 11(2):5–50. <https://doi.org/10.1016/j.pts.2009.12.002>
- Coratella G, Bellin G, Beato M, Schena F (2015) Fatigue affects peak joint torque angle in hamstrings but not in quadriceps. *J Sports Sci* 33(12):1276–1282
- Coratella G, Bellini V, Schena F (2016) Shift of optimum angle after concentric-only exercise performed at long vs. short muscle length. *Sport Sci Health* 12(1):85–90
- Dickin DC, Too D (2006) Effects of movement velocity and maximal concentric and eccentric actions on the bilateral deficit. *Res Q Exerc Sport* 77(3):296–303
- Häkkinen K, Kallinen M, Linnamo V, Pastinen UM, Newton R, Kraemer WJ (1996) Neuromuscular adaptations during bilateral versus unilateral strength training in middle-aged and elderly men and women. *Acta Physiol Scand* 158(1):77–88. <https://doi.org/10.1046/j.1365-201X.1996.523293000.x>
- Hay D, De Souza VA, Fukushima S (2006) Human bilateral deficit during a dynamic multi-joint leg press movement. *Hum Mov Sci* 25(2):181–191. <https://doi.org/10.1016/j.humov.2005.11.007>
- Howard JD, Enoka RM (1991) Maximum bilateral contractions are modified by neurally mediated interlimb effects. *J Appl Physiol* (1985) 70(1):306–316
- Jakobi JM, Cafarelli E (1985) Neuromuscular drive and force production are not altered during bilateral contractions. *J Appl Physiol* (1985) 1998(84):200–206
- Jakobi JM, Chilibeck PD (2001) Bilateral and unilateral contractions: possible differences in maximal voluntary force. *Can J Appl Physiol* 26(1):12–33. <https://doi.org/10.1139/h01-002>
- Kannus P, Beynnon B (1993) Peak moment occurrence in the range of motion during isokinetic extension and flexion of the knee. *Int J Sports Med* 14(8):422–426. <https://doi.org/10.1055/s-2007-1021203>
- Kawakami Y, Sale DG, Macdougall JD, Moroz JS (1998) Bilateral deficit in plantar flexion: relation to knee joint position, muscle activation, and reflex excitability. *Eur J Appl Physiol Occup Physiol* 77(3):212–216. <https://doi.org/10.1007/s004210050324>
- Khodiguian N, Cornwell A, Lares E, Dicaprio PA, Hawkins SA (2003) Expression of the bilateral deficit during reflexively evoked contractions. *J Appl Physiol* (1985) 94(1):171–178. <https://doi.org/10.1152/japplphysiol.00703.2002>
- Kubo K, Tsunoda N, Kanehisa H, Fukunaga T (2004) Activation of agonist and antagonist muscles at different joint angles during maximal isometric efforts. *Eur J Appl Physiol* 91(2–3):349–352. <https://doi.org/10.1007/s00421-003-1025-x>
- Kues JM, Rothstein JM, Lamb RL (1992) Obtaining reliable measurements of knee extensor moment produced during maximal voluntary contractions: an experimental investigation. *Phys Ther* 72(7):492–501
- Kuruganti U, Murphy P, Pardy T (2011) Bilateral deficit phenomenon and the role of antagonist muscle activity during maximal isometric knee extensions in young athletic men. *Eur J Appl Physiol* 111(7):1533–1539. <https://doi.org/10.1007/s00421-010-1752-8>
- Kuruganti U, Seaman K (2006) The bilateral leg strength deficit is present in old, young and adolescent females during isokinetic knee extension and flexion. *Eur J Appl Physiol* 97(3):322–326. <https://doi.org/10.1007/s00421-006-0188-7>
- Matkowsky B, Martin A, Lepers R (2011) Comparison of maximal unilateral versus bilateral voluntary contraction force. *Eur J Appl Physiol* 111(8):1571–1578. <https://doi.org/10.1007/s00421-010-1775-1>
- Oda S, Moritani T (1996) Interlimb co-ordination of force and movement-related cortical potentials. *Eur J Appl Physiol* 74(1–2):8–12
- Ohtsuki T (1983) Decrease in human voluntary isometric arm strength induced by simultaneous bilateral exertion. *Behav Brain Res* 7(2):165–178

25. Owings TM, Grabiner MD (1998) Fatigue effects on the bilateral deficit are speed dependent. *Med Sci Sports Exerc* 30(8):1257–1262
26. Owings TM, Grabiner MD (1998) Normally aging older adults demonstrate the bilateral deficit during ramp and hold contractions. *J Gerontol A Biol Sci Med Sci* 53(6):B425–B429
27. Post M, Van Duinen H, Steens A, Renken R, Kuipers B, Maurits N, Zijdwind I (2007) Reduced cortical activity during maximal bilateral contractions of the index finger. *Neuroimage* 35(1):16–27. <https://doi.org/10.1016/j.neuroimage.2006.11.050>
28. Rothstein JM, Lamb RL, Mayhew TP (1987) Clinical uses of isokinetic measurements. Critical issues. *Phys Ther* 67(12):1840–1844
29. Schantz PG, Moritani T, Karlson E, Johansson E, Lundh A (1989) Maximal voluntary force of bilateral and unilateral leg extension. *Acta Physiol Scand* 136(2):185–192
30. Simoneau-Buessinger E, Leteneur S, Toumi A, Dessurte A, Gabrielli F, Barbier F, Jakobi JM (2015) Bilateral strength deficit is not neural in origin; rather due to dynamometer mechanical configuration. *PloS One* 10(12):e0145077
31. Smith SS, Mayer TG, Gatchel RJ, Becker TJ (1985) Quantification of lumbar function. Part 1: Isometric and multispeed isokinetic trunk strength measures in sagittal and axial planes in normal subjects. *Spine (Phila Pa 1976)* 10(8):757–764
32. Taniguchi Y, Burle B, Vidal F, Bonnet M (2001) Deficit in motor cortical activity for simultaneous bimanual responses. *Exp Brain Res* 137(3–4):259–268
33. Vandervoort AA, Sale DG, Moroz J (1984) Comparison of motor unit activation during unilateral and bilateral leg extension. *J Appl Physiol Respir Environ Exerc Physiol* 56(1):46–51
34. Vandervoort AA, Sale DG, Moroz JR (1987) Strength-velocity relationship and fatiguability of unilateral versus bilateral arm extension. *Eur J Appl Physiol Occup Physiol* 56(2):201–205