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a b s t r a c t

The present study aimed to standardize isotonic (IT) and isokinetic (IK) eccentric exercises by equalizing the amount of work and the angular velocity at two intensity levels, to be able to compare specific effects of these exercise modes on the neuromuscular system. Fourteen subjects participated in three test sessions consisting of two IT and two IK sets on a customized isokinetic dynamometer. IT sets were comprised of 8 eccentric contractions of the knee extensors at 120% of the maximal repetition (1RM) in the first two sessions, and 100% in the third session. IK sets were performed at the same mean angular IT velocity and stopped when the amount of work performed corresponded to the IT set. External work, angular velocity and Root Mean Square (RMS) of electromyographic activity of three superficial muscles of the quadriceps femoris were calculated. Results showed concordance of work and angular velocity for each test session. Both modes involved the same number of repetitions at 120% and fewer repetitions in IK mode at 100% of 1RM. Work and RMS values remained steady in all sets. This study allowed the standardization of isotonic and isokinetic eccentric exercises, a first step before determining their specific effects on neuromuscular function.

1. Introduction

When muscles support a load torque that exceeds the muscular torque, an eccentric contraction is performed. The production of muscular force is associated with an active lengthening. This stretch of the elastic components of the muscle-tendon unit induces the production of high levels of torque during eccentric exercises. Such exercises are commonly used in training programs (Roig et al., 2009) and rehabilitation protocols (Rees et al., 2009). Numerous studies have focused on strength gains and physiological adaptations (e.g. muscular hypertrophy, changes in muscle architecture, rise in neural activation) induced by eccentric training (Blazevich et al., 2007; Guilhem et al., in press-a,b; Hortobagyi et al., 1996a,b; Housh et al., 1998; Komi and Buskirk, 1972; Roig et al., 2009). Eccentric loading has also been suggested to be an effective treatment protocol in the management of chronic tendinopathy, particularly of the Achilles and patellar tendons (Croisier et al., 2007; Kingma et al., 2007; Rees et al., 2009; Stanish et al., 1986). Although most of the studies found that eccentric exercises improve knee function (i.e. ability to undertake physical activity as often quantified by the VISA Score (Visentini et al., 1998)) and pain, the ability to recommend a specific protocol is limited due to the lack of comparative and controlled studies (Visnes and Bahr, 2007).

Eccentric exercises can be performed against a constant load (isotonic, IT) using body weight (i.e. body weight squat, squat on a decline board), dumbbells or weight lifting bars. During such tasks the device provides a constant resistance throughout the range of the muscle contraction, thus loading the muscles more strongly at the weakest joint angles. Although isoinertial or isoload actions more accurately reflect weight lifting actions (Abernethy et al., 1995; Caruso et al., 2005), this type of task is still often considered an isotonic movement in the literature. Eccentric exercises can also be performed at a constant velocity on an isokinetic (IK) dynamometer. In an IK contraction the velocity remains constant regardless of the resistance performed by the subjects. Consequently, the IK mode is hypothesized to maximally load the muscles through the entire range of motion. These differences in mechanical characteristics may induce different responses of the neuromuscular system. IT (Duclay et al., 2008; Housh et al., 1998) and IK (Hortobagyi et al., 1996a,b; Komi and Buskirk, 1972) eccentric trainings are recognized to improve muscle strength and increase muscle volume and activity. Nevertheless, a comparison between IT and IK eccentric modes in standardized protocol has not been performed. This lack of research may originate from the difficulty in designing protocols that allow for standardization of IT and IK eccentric exercises (Guilhem et al., in press-a,b).

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Previous studies comparing IT and IK concentric exercises have contradicting results regarding which method is most effective at increasing muscular strength (Kovaleski et al., 1995; Smith and Melton, 1981). The apparent discrepancies originate from the protocols set up to compare these two training modes. Authors interested in such a comparison during concentric exercise have discussed several key points. For instance, Smith and Melton (1981) suggested that equalization of the external amount of work performed was a critical question (Smith and Melton, 1981). Moreover, the neuromuscular adaptations induced by eccentric training are highly specific to the angular velocity (Roig et al., 2009). These two parameters were used by recent studies to compare IT and IK standardized concentric exercises. The results showed a different behavior of the neural drive in response to each mode (Remaud et al., 2009). Results showed that both modes involved the same number of repetitions to perform the same amount of external work when IT exercise was set at 80% of the maximal repetition (1RM) (Remaud et al., 2005). However, the effect of exercise intensity (i.e. external load commonly calculated as a percentage of 1RM or MVC) on the standardization procedure has not yet been considered. Yet external load affects the external torque produced, the amount of work produced for each repetition and the number of repetitions needed to reach the total external work target. Thus the external load could have an effect on the standardization method by modifying the number of repetitions required for each mode. Recently, we designed a new device to perform IT and IK eccentric exercises on the same ergometer which allows for the acquisition of mechanical parameters (i.e. position, torque, angular velocity) under comparable conditions (Guilhem et al., in press-b). The aim of the present study was to develop a standardization methodology for performing IT and IK eccentric exercises by equalizing the amount of external work and the angular velocity performed during both modes. This method was also tested at two intensities commonly used in eccentric exercise to determine potential effects of exercise intensity on the standardization procedure.

2. Methods

2.1. Subjects

Fourteen healthy male subjects without any previous history of knee injury volunteered to participate in this study. The mean (±SD) age, height and body mass of the subjects were 21.5 ± 2.7 years, 179.7 ± 5.7 cm and 77.7 ± 9.4 kg, respectively. Subjects were informed regarding the nature, the aims, the risks and discomfort associated to the study before they gave their written consent to participate. This study was approved by a local ethics committee and conducted according to the Helsinki Declaration (1964 revised in 2001).

2.2. Dynamometry

Eccentric sessions were performed on a customized ergometer that was previously validated (Guilhem et al., in press-b). Briefly, a plate-loaded resistance training device was implemented to an isokinetic dynamometer (Biodex System 3 Pro, Shirley, NY, USA) to acquire mechanical parameters on the same ergometer in both modes. In IT mode, a constant load by guided masses linked to the dynamometer attachment by a steel wire was applied to the lever arm (Fig. 1). In these conditions, subjects performed eccentric contractions of the knee extensors against a constant torque applied by the resistance training device through the entire range of motion. In the IK mode, subjects performed eccentric contractions at a constant angular velocity. This device also allowed us to stop the exercise when the predetermined amount of work

Fig. 1. Picture of the device. A plate-loaded resistance training device was integrated to an isokinetic dynamometer Biodex System 3 (a). Loads (c) were linked to the dynamometer attachment by a wire. The wire passed through two pulleys and followed a half-circle metal piece (b) fixed to the dynamometer attachment. (a) Dynamometer – Biodex System 3 Pro; (b) half-circle metal piece; (c) loads.

was achieved through the use of visual feedback. Ergometer settings were recorded and reproduced during all sessions. Mechanical signals were recorded at a sampling frequency of 1000 Hz.

2.3. Electromyography

Bipolar surface electromyography (EMG) signals were recorded during each test session from surface EMG sensors (DE-2.1, Delsys®, Boston, MA, USA) on the *vastus lateralis* (VL), *vastus medialis* (VM) and *rectus femoris* (RF) muscles. Each EMG sensor was made of two parallel silver (Ag–AgCl) bars with a length of 10 mm. The inter-bar distance was 10 mm. Electrode-skin impedance was reduced using standard skin preparation procedures (Maisetti et al., 2002). According to the SENIAM recommendations (Hermens et al., 2000), surface EMG sensors were placed between the distal tendon and the innervation zone parallel to the direction of the muscle fibers. The positions of the electrodes were labeled with indelible ink during the first test session to ensure the same electrode positioning in each test session. EMG signals were pre-amplified (gain = 10) at the sensor level and sampled at 1000 Hz via an *A/D* converter (Bagnoli 16 EMG System, Delsys®, Boston, MA, USA; input impedance > 10^{15} X; common mode-rejection ratio at 60/10 Hz = 92 dB; gain = 1000; bandwidth = 0–400 Hz).

2.4. Experimental design

Each subject participated in a familiarization session and three test sessions 1 week apart.

2.4.1. Familiarization session

The familiarization session allowed the subjects to be familiarized with the customized ergometer and the IT and IK modes. After a 5 min warm-up on a cycloergometer (100 W) subjects were seated on the ergometer so that the hip was flexed to 85° (0° = full hip extension) and began a specific warm-up. After 1 min of rest, subjects performed one maximal isometric voluntary contraction (MVC) in order to determine the first load for the determination of the maximal load the subject could lift in a single concentric contraction (1RM). The first load corresponded to 70% of the MVC. The load was then progressively increased with a 1 kg load after a 1 min rest. 1RM was the last load the subjects could lift on the whole range of motion (90–30°, 0° = full knee extension) with a 5° tolerance. Subjects then completed 10 submaximal eccentric contractions in IT and IK modes before they performed the protocol detailed in Table 1.

Table 1
Design of the experimental protocol. 1RM: maximal repetition; MVC: maximal isometric voluntary contraction; $IT_1 - IT_2$: first and second isotonic set; $IK_1 - IK_1$: first and second isokinetic set; $\bar{\chi}_1 - \bar{\chi}_1$: mean of angular velocity in IT_1 and IT_2; $n_1 - n_2$: number of repetitions performed in IK_1 or IK_2 to reach the amount of work performed in IT_1 or IT_2.

Order	Familiarization session	Test session 1	Test session 2	Test session 3
1	Warm-up			
2	1RM			
3	1 min rest	1 min rest		1 min rest
4	2 MVC	IT_1: 8 repetitions		IT_1: 8 repetitions
	1 min rest	120% 1RM		100% 1RM
5	IT_1: 8 repetitions 120% 1RM	5 min rest		5 min rest
6	5 min rest	IK_1: n_1 repetitions $\bar{\chi}_1$		IK_1: n_1 repetitions $\bar{\chi}_1$
7	2 MVC 1 min rest	5 min rest		5 min rest
8	IK_1: n_1 repetitions $\bar{\chi}_1$	IT_2: 8 repetitions 120% 1RM	IK_2: n_1 repetitions $\bar{\chi}_2$	IT_2: 8 repetitions 100% 1RM
9	1 min rest	5 min rest	5 min rest	5 min rest
10	2 MVC	IK_2: n_2 repetitions $\bar{\chi}_2$	IT_2: 8 repetitions 120% 1RM	IK_2: n_2 repetitions $\bar{\chi}_2$

2.4.2. Test sessions

In each test session, subjects warmed-up and then the 1RM was determined in the same manner as during the familiarization session. In the first (TS1) and second (TS2) test session, subjects performed two IT sets at 120% of the 1RM and two IK sets of maximal eccentric contractions of the knee extensors from a knee angle ranging from 30° to 90°, following the experimental protocol presented in Table 1. In TS2, the second IK set was performed before the second IT set to test the effect of order on the standardization procedure. In the most of training protocols, supra-maximal eccentric sessions are preceded by lower exercise intensity. Numerous studies have shown an effect of exercise intensity (i.e. external load) on muscle activity and consequently on the external torque produced (Babault et al., 2001; Komi et al., 1987; Linnamo et al., 2003). Thus, in order to test the effect of external load on the standardization procedure, the third test session (TS3) consisted in the same protocol as in TS1, but IT sets were performed at 100% of the 1RM and IK sets were still performed in maximal conditions.

2.5. Data analysis

2.5.1. Mechanical data

Torque measurements were gravity and inertia corrected through the overall range of motion (Aagaard et al., 1995; Guilhem et al., in press-b). For each repetition, the amount of external angular work (W) and the mean angular velocity $(\bar{\chi})$ were determined on the whole range of motion (Remaud et al., 2005). W was calculated at each time interval from the muscular torque produced by the subject (T_{mus}) and the angular position (θ), as expressed by the Eq. (1):

$$W = \int_{\theta_0}^{\theta_n} T_{mus} \cdot d\theta \qquad (1)$$

W: work (J); T_{mus}: muscular torque (N m); θ: angle (rad).

For modes comparison, muscular torque and angular velocity were averaged over 5° windows.

2.5.2. Standardization procedure

IT sets consisted of 8 repetitions at 120% of 1RM for the familiarization session, as well as the first and second test sessions. IT mode was set at 100% of the 1RM in the third test session. IT angular velocity ranged from 20 to 75°s^{-1} across trials. In each IK set, subjects performed n maximal repetitions at a velocity similar to the mean velocity measured during the corresponding isotonic set; where n represented the number of repetitions necessary to reach the amount of work performed in the corresponding isotonic set at the same mean angular velocity (Table 1) (Remaud et al., 2005).

2.5.3. EMG data

SEMG data were band-pass filtered using a second order Butterworth filter (bandwidth: 6–400 Hz) to remove any motion artefact. The MVC with the highest maximal torque was considered for further analysis. The maximal Root Mean Square (RMS) value was calculated over a time period of 200 ms (i.e. 100 ms before and after the time to peak torque) from EMG signals of each muscle (Remaud et al., 2009). For each repetition and for each muscle, a mean RMS value was determined on a time window corresponding to the time required to complete the range of motion comprising the isotonic and isokinetic steady states (from 35° to 80°). RMS values of EMG activity of quadriceps femoris were normalized to the maximal RMS value obtained during MVC. RMS values of the three superficial knee extensors were averaged to express a mean knee extensors RMS (Hakkinen et al., 1991).

2.6. Statistical analysis

Normality of data was tested using a Kolmogorov–Smirnov test. Two-way ANOVAs (mode × angle) for repeated measures were used to test differences in torque and angular velocity between both exercise modes. The level of concordance for the amount of work and the mean angular velocity between IT and IK modes was assessed using Bland–Altman plots. According to Bland and Altman, the limits of agreement were defined as the mean difference ± 1.95 SD of the difference, (Bland and Altman, 1986). A Wilcoxon signed rank test was used to analyze potential differences in the number of repetitions between both modes. Trial-to-trial reproducibility of work was determined during the first set of TS2 by calculating the intraclass correlation coefficient (ICC), the standard error of measurement (SEM) and the coefficient of variation (CV). One-way ANOVA for repeated measures was used to test effect of eccentric sets on MVC peak torque. Three-way ANOVAs (mode × set × repetitions) for repeated measures were used to test potential differences in work, angular velocity and muscular activity level between repetitions in each set for both mode. If the sphericity assumption in repeated measures ANOVAs was violated (Mauchly's test), then a Geisser–Greenhouse correction was used. *Post-hoc* tests were performed by means of Newman–Keuls procedures. For all tests, the critical level of significance was set at $p < 0.05$. Results are presented as mean ± SE.

3. Results

3.1. Comparison of IT and IK eccentric exercises

The two-way ANOVAs revealed a mode × angle interaction effect for the torque-angle ($p < 0.0001$) and velocity-angle ($p < 0.0001$) relationships at all test sessions. *Post-hoc* analysis showed significant differences between IT and IK mode in torque–angle relationship on the whole range of motion except at 55° and 90° at 120% of 1RM and at 50° and 90° at 100% of 1RM (Fig. 2A). The velocity–angle relationship showed significant differences between IT and IK mode from 30° to 65° and at 90° at 120%, and from 30° to 65° and from 80° to 90° at 100% (Fig. 2B).

3.2. Controlled parameters

Bland–Altman analysis showed concordance between IT and IK modes for the amount of work (Fig. 3A) and for the mean angular velocity (Fig. 3B) as illustrated by the low bias values for the amount of work (6.8 J at 120%; -2.7 J at 100%) and angular velocity ($-0.9°s^{-1}$ at 120%; 1.8°/s at 100%). IT angular velocity variation was equal to $±8.2°s^{-1}$ at 120% of 1RM and $±4.2°s^{-1}$ at 100% of 1RM across trials. Changing the order between IT and IK sets induced a lower, but acceptable concordance for amount of work (bias = 6.8 J; CI 95%: [-59.5–73.0]) and angular velocity (bias = $-0.9°s^{-1}$; CI 95%: [-7.1–7.4]). ICC and SEM values demonstrated

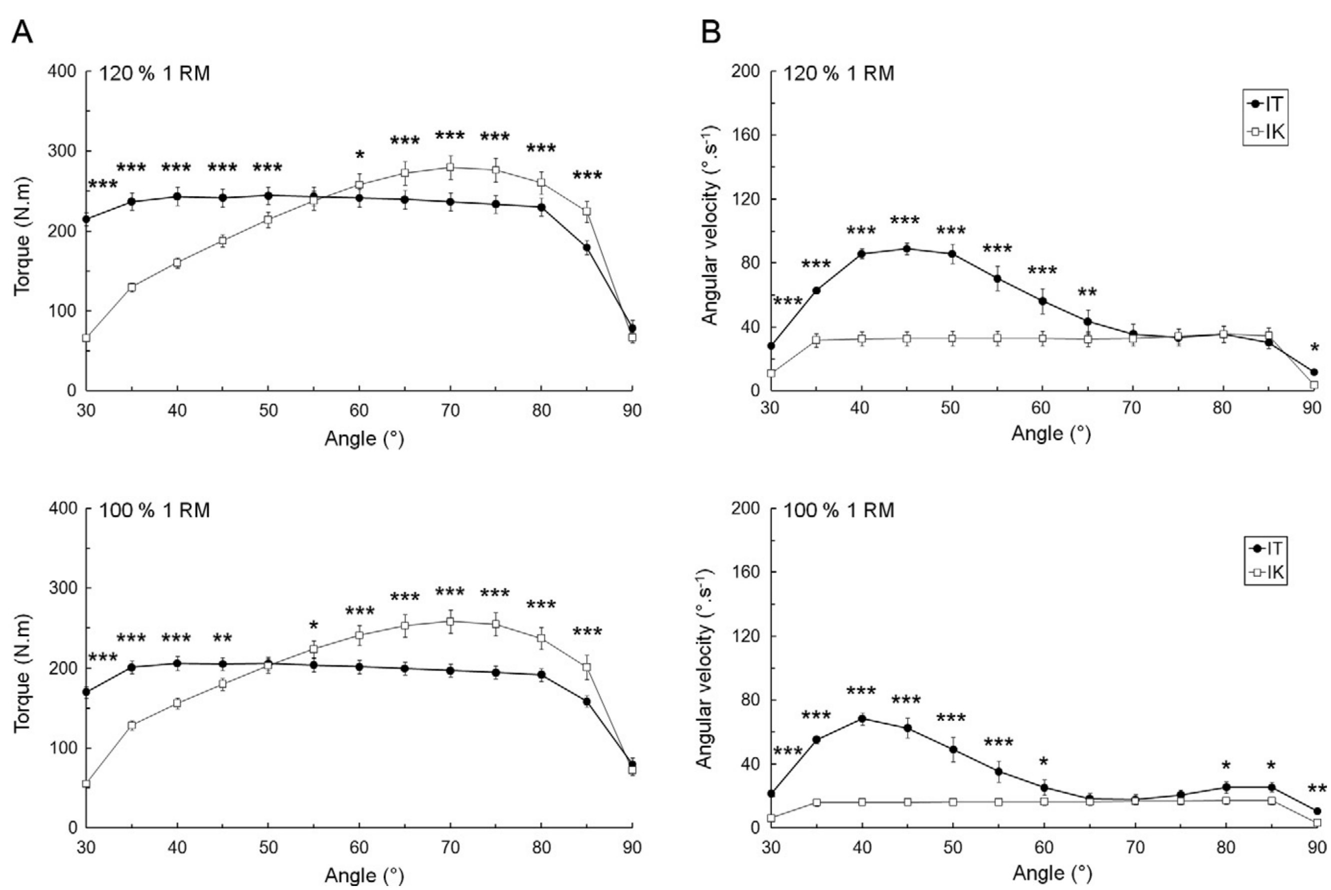

Fig. 2. Muscular torque–angle relationships (A) and angular velocity–angle (B) relationship for isotonic (IT) and isokinetic (IK) eccentric exercises when isotonic mode is performed at 120% (top) and 100% (bottom) of the maximal repetition (1RM). All values are means ± SE. *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$ (Newman–Keuls *post-hoc* test).

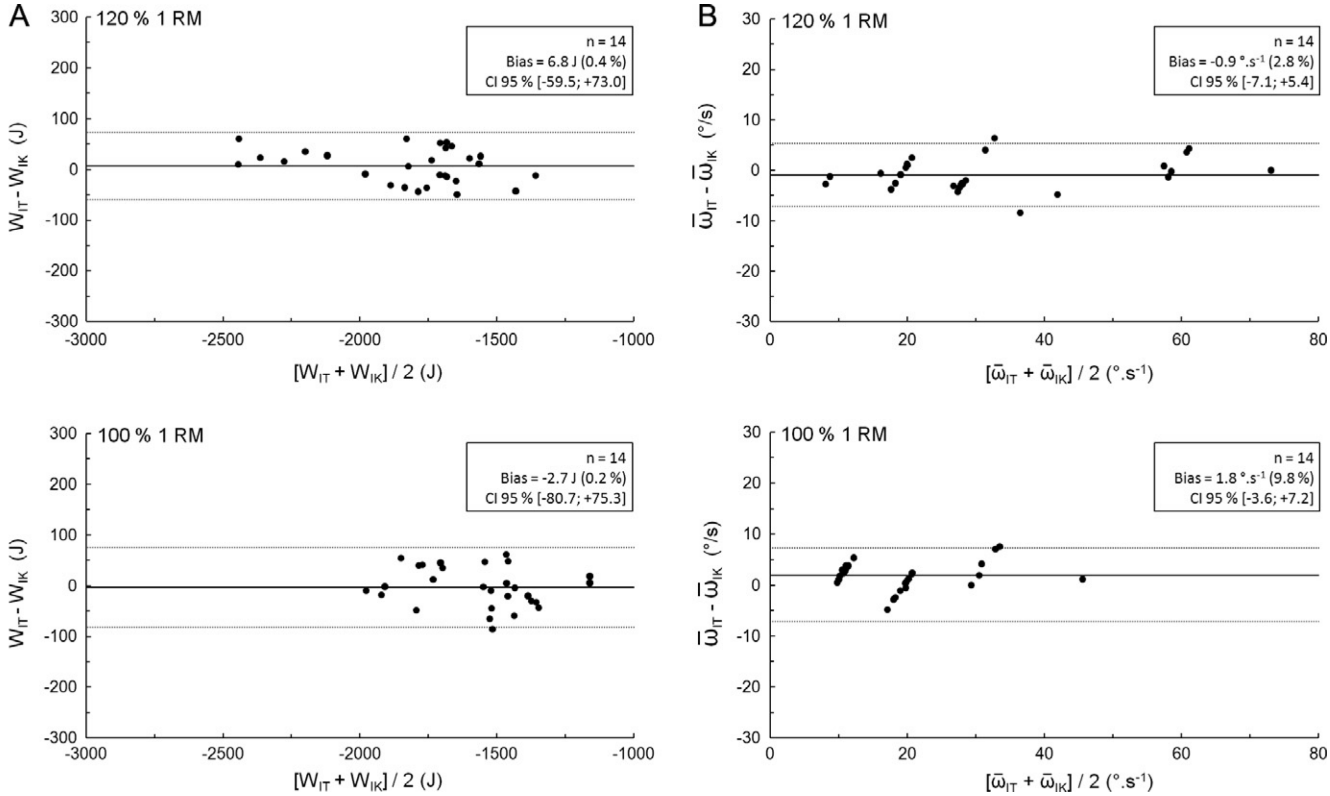

Fig. 3. Bland–Altman plots for the amount of work performed (A) and mean angular velocity (B) between isotonic (IT) and isokinetic (IK) eccentric exercises, when isotonic mode is performed at 120% (top) and 100% (bottom) of the maximal repetition (1RM). Isotonic sets were performed before isokinetic sets. W_{IT}: amount of work performed in isotonic mode; W_{IK}: amount of work performed in isokinetic mode; $\overline{\chi_{IT}}$: mean angular velocity in isotonic mode; $\overline{\chi_{IK}}$: mean angular velocity in IK mode; CI: confidence interval.

Table 2
Mean total amount of external angular work, mean angular velocity of movement and number of repetitions performed during sets of eccentric contractions in isotonic and isokinetic modes.

Controlled parameter	Test session	IT load (% 1RM)	IT mode		IK mode	
			Set 1	Set 2	Set 1	Set 2
Amount of work (J)	1	120	-1845 (±87)	-1799 (±80)	-1857 (±91)	-1801 (±83)
	2	120	-1860 (±81)	-1837 (±80)	-1863 (±78)	-1777 (±91)
	3	100	-1566 (±63)	-1567 (±63)	-1565 (±67)	-1563 (±64)
Angular velocity (°s^{-1})	1	120	28.8 (±4.2)	34.7 (±6.0)	30.1 (±4.3)	35.2 (±5.5)
	2	120	32.1 (±4.6)	34.4 (±4.6)	30.9 (±4.0)	35.0 (±5.8)
	3	100	20.7 (±3.2)	18.7 (±2.3)	18.4 (±3.1)	17.3 (±2.3)
Number of repetitions	1	120	8.0 (±0.0)	8.0 (±0.0)	7.7 (±0.2)	7.9 (±0.2)
	2	120	8.0 (±0.0)	8.0 (±0.0)	8.1 (±0.2)	7.8 (±0.2)
	3	100	8.0 (±0.0)	8.0 (±0.0)	7.3* (±0.3)	6.7* (±0.6)

1RM: maximal repetition. TS: test session. Results are presented as mean ± SE. * $p < 0.05$.

a satisfying reproducibility for the amount of work (ICC = 0.96; SEM = 75.6 J; CV = 3.0%).

3.3. Number of repetitions

In these standardized conditions, no statistical differences were observed in the number of repetitions performed in IT mode at 120% of 1RM and IK mode. When IT sets were performed at 100% of 1RM, subjects performed more repetitions than in the corresponding IK sets (8.0 and 8.0 in IT vs. 7.3 and 6.7 in IK mode; $p = 0.02$ for set 1; $p = 0.005$ for set 2; Table 2).

3.4. Performance changes

Three-way ANOVAs revealed no differences in the amount of work performed ($p = 0.22$ at 120%; $p = 0.85$ at 100%) and the mean

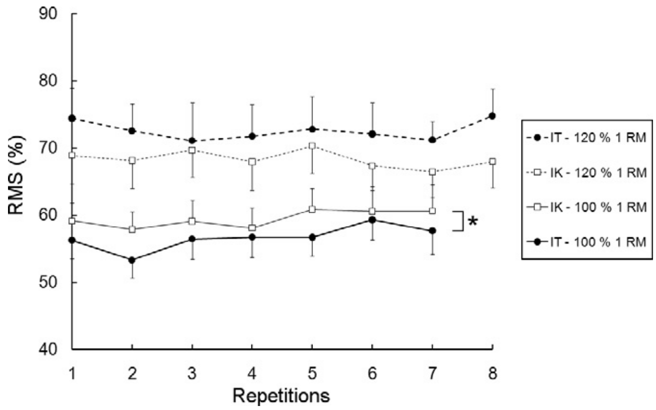

Fig. 4. Root Mean Square (RMS)-repetition relationships for isotonic (IT) and isokinetic (IK) eccentric exercises, when isotonic mode is performed at 100% and 120% (dashed line) of the maximal repetition (1RM). All values are means ± SE. *$p < 0.05$.

angular velocity ($p = 0.33$ at 120%; $p = 0.78$ at 100%) between repetitions for the two solicitation modes. During familiarization session, we observed no differences in peak torque of the two MVCs performed before or after the IT set.

3.5. EMG activity-repetitions relationships

The three-way ANOVA on RMS values of EMG activity of quadriceps femoris revealed no set ($p = 0.24$ at 120%; $p = 0.77$ at 100%) or repetition effect ($p = 0.86$ at 120%; $p = 0.86$ at 100%). RMS values for the IK mode were higher at 100% of 1RM ($p = 0.04$; Fig. 4).

4. Discussion

The main purpose in the present study was to develop a method to equalize the amount of work and the mean angular velocity in isotonic and isokinetic eccentric exercises. This procedure was designed to be able to compare the effects of IT and IK eccentric exercises on the neuromuscular system during an exercise session and after a training period in future studies. The standardization procedure showed the concordance of amount of work and angular velocity between IT and IK modes. In these standardized conditions, both modes involved the same number of repetitions when IT eccentric exercise was set at 120% of 1RM. More repetitions were executed in IK mode when IT sets were performed at 100% of 1RM.

The comparison analysis showed that IT and IK eccentric exercises elicit different mechanical characteristics, including torque and movement velocity (Fig 2). In fact, muscular torque exerted in the IT mode was constant from 35° to 80° whereas it increased in IK mode from 30° to 70° before decreasing until 90°. Muscular torque was higher in the IT mode at the extended joint angles while it was higher in IK mode at the flexed joint angles. Angular velocity was higher in IT mode in extended and at flexed joint angles at both exercise intensities.

These differences in mechanical load could induce specific effects on neuromuscular system, thus requiring the development of a standardization procedure. Such an approach was successfully undertaken in concentric contractions to equalize external work and movement velocity of IT and IK modes (Remaud et al., 2005). The procedure developed in our study consisted in the next step of this work by implementing the method to eccentric exercise. Previous eccentric protocols using submaximal loads (i.e. <100% 1RM) were unable to progressively increase external resistance for optimal eccentric training effects to take place (Hortobagyi and Katch, 1990; Johnson, 1972). Therefore the present study used maximal and supra-maximal loads of 100% and 120% of 1RM that are commonly prescribed in eccentric exercise (Brandenburg and Docherty, 2002; Colson et al., 1999). IT and IK eccentric exercises were standardized by equalizing the amount of work and angular velocity in both modes. Our results showed concordance of the two controlled parameters (i.e. work, angular velocity) between modes, regardless of the order in which they were performed. The standardization procedure also induced a similar duration of eccentric contraction in IT and IK modes. Therefore, it could be assumed that the IT and IK eccentric exercises were standardized for these two parameters. The amount of work performed during eccentric sessions was consistent between each set and no differences existed in maximal isometric peak torque before IT and before IK sets. Consequently, subjects conserved similar capacity of force production in IT and IK sets. These results paralleled the constant activation level of the knee extensors muscles.

In these standardized conditions, the same number of repetitions were necessary to reach the amount of external work performed in the corresponding IT sets at 120% of 1RM, thus confirming our hypothesis at this exercise intensity. This is in accordance with previous work performed on IT and IK modes at lower intensity with concentric contractions (Remaud et al., 2005). The higher amount of work performed in our study than in the study of Remaud et al. (2005) could be attributed to the higher torque levels the muscles can exert in eccentric contractions compared to concentric contractions. Nevertheless, it is clear that the exercise intensity had an effect on the standardization procedure, since fewer repetitions were needed in IK sets when IT sets were performed at 100% of 1RM. The muscular torque produced in the IT mode at 100% were lower than those produced at 120% of 1RM, resulting in a lower amount of work. Corresponding maximal eccentric contractions in the IK mode produced similar torque levels in all sessions. Consequently, subjects required fewer repetitions in IK mode to achieve the same amount of work as during IT sets performed at 100% of 1RM. These results are supported by the higher RMS values in IK sets when IT sets were performed at 100% of 1RM. Indeed, subjects seem to recruit fewer motor units in IT mode in this condition and in turn, produced lower levels of torque.

Initially suggested by Stanish et al. (1986), eccentric exercise is a popular non-invasive treatment for tendinopathy. IT (Jonsson and Alfredson, 2005; Visnes and Bahr, 2007; Young et al., 2005) and IK (Croisier et al., 2007; Stanish et al., 1986) modes have been prescribed to manage this disability that is a major component of clinical injuries in sport and in the general population. Although chances of improvement of knee function and pain are estimated to be 50–70%, comparative studies have to date failed to determine the most effective protocols because of limitations in the study design (Langberg and Kongsgaard, 2008; Meyer et al., 2009; Rees et al., 2009; Visnes and Bahr, 2007). Young et al. (2005) attempted to compare these protocols. However, several parameters were uncontrolled and non-standardized. Moreover, IT and IK eccentric exercises are included in resistance training programs to achieve an increase in muscular strength. However, comparative analysis led in the present study showed significant disparities between both modes in torque and angular velocity-angle relationships. Such differences suggest specific neuromuscular adaptations in response to each mode. Future research is needed to compare the effectiveness of IT and IK modes during eccentric contraction in rehabilitation and training by equalizing work and movement velocity with the present method. Moreover, testing with female and elderly subjects would allow standardization of the procedure on different populations. Indeed the age and gender of participants could have an effect on muscle function and potentially impact this method developed using college-aged male subjects.

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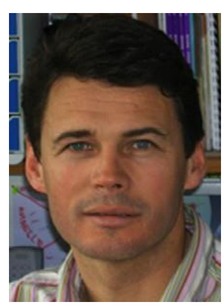

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