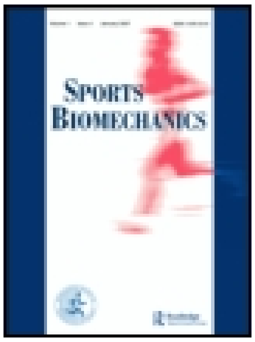

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Comparison of two methodological approaches for the mechanical analysis of single-joint isoinertial movement using a customised isokinetic dynamometer

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ABSTRACT
Compared to isokinetic and isometric tests, isoinertial movements have been poorly used to assess single-joint performance. Two calculation procedures were developed to estimate mechanical performance during single-joint isoinertial movements performed on a customised isokinetic dynamometer. The results were also compared to appreciate the effects of measurement systems and calculation procedures. Five participants performed maximal knee extensions at four levels of resistance (30, 50, 70 and 90% of the one-repetition maximum, 1-RM). Joint angular velocity and torque were assessed from customised isokinetic dynamometer measures (method A) and from weight stack kinematic (method B). Bland–Altman plots and mean percent differences (M_{diff}) were used to assess the level of agreement for mean and peak angular velocity and torque. A Passing–Bablok regression was performed to compare the angular velocity-angle and torque-angle relationships computed from the two analysis methods. The results showed a high level of agreement for all mechanical parameters ($M_{diff} < 6\%$ for all parameters). No statistically significant differences were observed between methods A and B in terms of angular velocity-angle and torque-angle relationships except at 30% of 1-RM for the torque-angle relationship. Both methodologies provide comparable values of angular velocity and torque, offering alternative approaches to assess neuromuscular function from single-joint isoinertial movements.

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KEYWORDS
Torque; angular velocity; leg extension; kinematic; isokinetic dynamometer

Introduction

Isoinertial movements are largely used to assess force production capabilities for sports training and rehabilitation purposes (McMaster, Gill, Cronin, & McGuigan, 2014). In such tests, the participants intend to accelerate a constant external load throughout the entire range of motion in order to produce maximal velocity and torque output (Cronin, McNair,

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& Marshall, 2003). Most of the time, the movement patterns (e.g. bench press, squat jump, clean …) and strength-training devices (e.g. using a Smith machine or a Plyometric Power System) have been chosen and adapted in order to allow for ballistic movements, so that maximal isoinertial performance has been exclusively assessed from multi joint linear movement (for review, see McMaster et al., 2014).

On the other hand, mechanical performance in single-joint movements has been widely assessed to characterise the profile of a specific muscle group, from torque-velocity and torque-angle relationships (Russell, Quinney, Hazlett, & Hillis, 1995), or detect potential imbalances between muscle groups (Holcomb, Rubley, Lee, & Guadagnoli, 2007), quantifying agonist–antagonist ratio (Evangelidis, Pain, & Folland, 2015) and side to side asymmetry (Maffiuletti, Bizzini, Widler, & Munzinger, 2010). For that purpose, single-joint maximal performance has been measured from isometric or isokinetic tests which are unsuitable for athletic movements (Abernethy, Wilson, & Logan, 1995). For the most part, the use of single-joint isoinertial movement is limited because traditional strength-training device does not allow to perform maximal contraction on the whole range of motion (Cronin et al., 2003). As with multi joint movements, the assessment of isoinertial maximal performance requires adapting the single-joint strength-training device.

In a recent study, Guilhem, Cornu, Nordez, and Guével (2010) have developed a customised isokinetic dynamometer allowing isoinertial leg extension exercise. This device benefits from the cushioning mechanism of the isokinetic dynamometer, ensuring that the participant could exert maximal torque on the whole range of motion and in a safe condition, providing a useful tool to perform single-joint isoinertial movements. However, their mechanical analysis was designed for high load eccentric contractions and requires being adapted to accelerative movements, including the contribution of the lower leg and attachment moment of inertia to the joint torque.

With this device, the mechanical analysis can be performed from the weight stack kinematics using the approach of Bosco et al. (1995) adapted for rotational motion (Biscarini, 2012; Rahmani et al., 1999) or from data directly provided by the dynamometer (Guilhem et al., 2010). However, each one involves specific measurement systems and calculation procedures which were shown to influence the outcomes (McMaster et al., 2014).

The current study developed and compared methods for mechanical analysis of single-joint isoinertial exercises using a customised isokinetic dynamometer. Method A was designed to assess the mechanical performance of single-joint isoinertial movements from customised isokinetic dynamometer measures (adapted from Guilhem et al., 2010) and method B to assess the same variables but instead analyses weight stack displacement (adapted from Bosco et al., 1995). Mean joint angular velocity, peak joint angular velocity, angular velocity-angle and torque-angle relationships were computed and compared between the two mechanical analysis methods. It was hypothesised that: (i) mean angular velocity and mean torque computed for method A and B would show a high level of agreement; (ii) the level of agreement between the two methods would be higher for mean values than the level of agreement for peak values; and (iii) the angular velocity-angle and torque-angle relationships could exhibit slight differences according to the indirect estimation of joint kinematic and external torque in method B.

Methods

Participants

Five healthy men (26 ± 3 years, height 181 ± 6 cm, body mass 74 ± 7 kg) volunteered as participants in the study. They were informed regarding the nature, aims and risks associated with the experimental procedure before they gave their written consent to participate. The study was approved by the local ethics committee (Rennes Ouest V – CPP-MIP-003) and was conducted in accordance with the declaration of Helsinki (2001).

Equipment

The study used a customised isokinetic dynamometer (Figure 1), previously validated in eccentric conditions and described in details (Guilhem et al., 2010). Briefly, a weight stack was integrated to an isokinetic dynamometer (Biodex Medical Systems, Shirley, NY, USA) to perform isoinertial exercises. The weight stack was connected to the leg attachment by a cable crossing 2 pulleys and following a half-circle metal piece (radius R = 0.395 m)

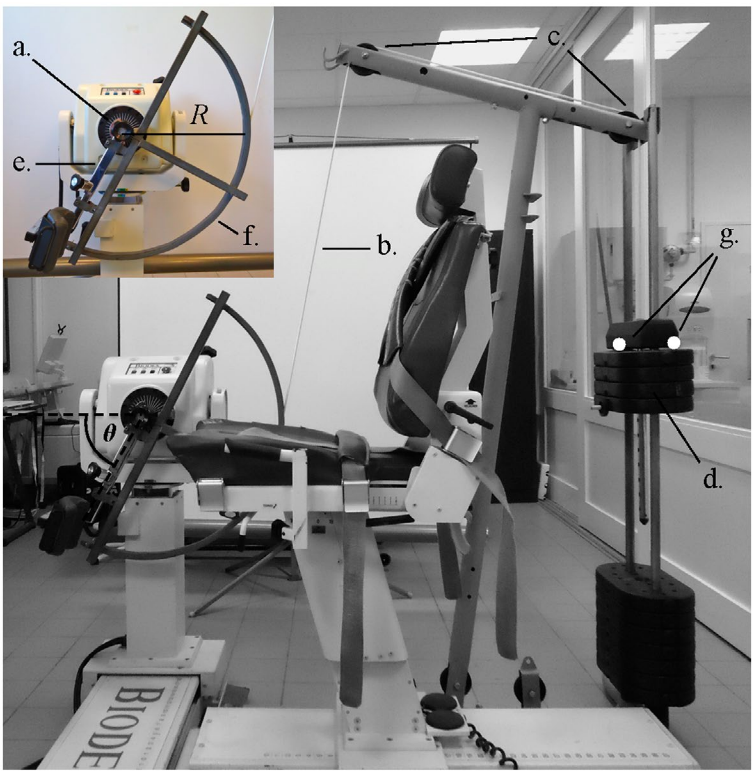

Figure 1. Customised isokinetic dynamometer. A plate loaded resistance training device was integrated to an isokinetic dynamometer Biodex System 3 Pro (a). A cable (b) passes through 2 pulleys (c), linking the weight stack (d) to the rotating system composed of the isokinetic dynamometer resistance lever (e) and a semicircular circle metal component (f) (radius $R = 0.395$ m). The isokinetic dynamometer provided the mechanical data for the rotating system while two reflective markers (g) allowed for the calculation of weight stack displacement using a motion capture system (Optitrack, NaturalPoint, OR, USA).

fixed to the resistance lever. The validity of the torque induced by the weight stack was previously established (Guilhem et al., 2010) and verified before the experiment (systematic bias = 20.1 Nm; mean percent difference = 1.7%). For knee extension movement, the dynamometer was set in isokinetic mode with an unachievable preset angular velocity so that the dynamometer does not influence the movement apart from the end of the ranges of motion (i.e. from 25° to 0° for higher angular velocity). After each knee extension, the motor of the dynamometer returned the leg to the initial position (i.e. lever arm at 95°).

Calculation procedure

Fundamental principle of dynamics

During the single-joint isoinertial movement, the torque balance applied on the *{leg + resistance lever}* system is equal to the product of the constant moment of inertia J and the angular acceleration $\ddot{\theta}$ of the system:

$$T_{\text{joint}} - T_{\text{att}} - T_{\text{leg}} - T_{\text{cable}} - T_{\text{dyn}} = J \cdot \ddot{\theta} \quad (1)$$

$$T_{\text{joint}} = J \cdot \ddot{\theta} + T_{\text{att}} + T_{\text{leg}} + T_{\text{cable}} + T_{\text{dyn}} \quad (2)$$

where T_{joint} is the joint torque produced by the participant (in Nm); T_{att}, the torque due to the weight of the attachment (resistance lever and half-circle metal piece; in Nm); T_{leg}, the torque due to the weight of the lower leg (shank and foot; in Nm); T_{cable}, the torque exerted by the cable force at the attachment point with the half-circle metal piece (in Nm); T_{dyn}, the torque due to the resistance produced by the dynamometer. The knee joint centre of both analysis methods described below was considered to coincide with the resistance lever centre of rotation. Each element of Equation (2) was estimated from an isokinetic dynamometer-based approach (method A) or a weight stack kinematic-based approach (method B) for computing T_{joint}. Calculations of $\ddot{\theta}$, J, T_{att}, T_{leg} and T_{cable} using both methods are described in detail below and summarised in the Table 1. T_{dyn} was instantaneously provided by the dynamometer. A pilot study showed that the contribution of T_{dyn} to the resistive torque was lower than 5 Nm between 95° and 25°.

Method A

Angular position θ was measured from the isokinetic dynamometer and correspond to the angle between the horizontal (0°) and the resistance lever during the movement. θ was differentiated to obtain angular velocity $\dot{\theta}$ and differentiated again to obtain angular acceleration $\ddot{\theta}$.

T_{att} was measured by moving the attachment over the complete range of motion using the passive mode of the isokinetic dynamometer (angular velocity = 5°/s). The torque was then modelled as a function of angular position with a quadratic function ($R^2 = 0.99$).

T_{leg} was computed as follows using the isokinetic dynamometer measurement of T_{leg} at a given angle α:

$$T_{\text{leg}} = \frac{T_{\text{leg}}(\alpha) \times \cos\theta}{\cos\alpha} \quad (3)$$

Table 1. Recap chart for methods A (isokinetic dynamometer-based approach) and B (weight stack kinematic-based approach).

	Method A		Method B	
	Mathematical formula	Specific parameters	Mathematical formula	Specific parameters
$\theta, \dot{\theta}, \ddot{\theta}$	$\dot{\theta}$ and $\ddot{\theta}$ obtained by differentiating θ	θ measured from isokinetic dynamometer measurements	$\theta = \theta_s - \frac{d}{R} \times \frac{180}{\pi}$	d estimated from weight stack kinematic
			$\dot{\theta}$ and $\ddot{\theta}$ obtained by differentiation and double differentiation	$R = 0.395$ m
				$\theta_s = 95^\circ$
J	$J = J_{leg} + J_{att}$	J_{leg} estimated from anthropometrical data (De Leva, 1996)	Same calculation method than method A (J_{att} could also be provided by the manufacturer)	
		J_{att} estimated from isokinetic dynamometer measurements (preliminary study)		
T_{att}	T_{att} modeled with a quadratic function ($R^2 = 0.99$)	T_{att} measured on the complete range of motion using the passive mode of the isokinetic dynamometer	$T_{att} = W_{att} \times LA_{att}$	m_{att} measured from an electronic scale
			$W_{att} = m_{att} \times g$	$g = 9.81$ m/s^2
			$LA_{att} = \sin\theta \cdot X_{att} + \cos\theta \cdot Y_{att}$	θ measured from weight stack kinematic
				(X_{att}, Y_{att}) estimated experimentally (could be provided by the manufacturer)
T_{leg}	$T_{leg} = \frac{T_{leg}(\alpha) \times \cos\theta}{\cos\alpha}$	$\alpha = 60^\circ$	$T_{leg} = W_{leg} \times LA_{leg}$	m_{leg} and (X_{leg}, Y_{leg}) estimated from anthropometrical data (De Leva, 1996)
		$T_{leg}(\alpha)$ measured from isokinetic dynamometer at a 60° angle	$W_{leg} = m_{leg} \times g$	$g = 9.81$ m/s^2
		θ measured from isokinetic dynamometer during the movement	$LA_{att} = \sin\theta \cdot X_{att} + \cos\theta \cdot Y_{att}$	θ measured from weight stack kinematic
T_{cable}	$T_{cable} = J_{WS} \cdot \theta + T_{WS}$	T_{WS} modelled from isokinetic dynamometer measurements (preliminary study)	$LA_{leg} = \sin\theta \cdot X_{leg} + \cos\theta \cdot Y_{leg}$	a measured from weight stack kinematic
	$J_{WS} = m \cdot R^2$		$T_{cable} = (m \cdot a + F_f + m \cdot g) \times R$	F_f estimated from weight stack kinematic in a preliminary study

where $T_{leg}(\alpha)$ is the torque due to the weight of the leg at a 60° angle. The resistance lever was placed at a 60° angle in order to prevent the influence of hamstring stiffness on the passive joint torque. T_{att} was subtracted from the torque measured by the isokinetic dynamometer to obtain $T_{leg}(\alpha)$.

T_{cable} was computed using the fundamental principle of dynamics applied on the *{cable + weight stack}* system (Figure 2A):

$$T_{cable} = J_{WS} \cdot \ddot{\theta} + T_{WS} \tag{4}$$

$$J_{WS} = m_{WS} \cdot R^2 \tag{5}$$

where J_{WS} is the system moment of inertia (in kg/m^2) and T_{WS}, the torque due to the weight stack when moving at a constant angular velocity (in Nm). The cable mass was negligible and the load was considered to act at the point of the attachment between the cable and the half-circle metal piece when computing J_{WS}. T_{WS} was measured with the isokinetic dynamometer set in passive mode at a constant angular velocity (5°/s) using eleven different loads from 9.20 to 57.78 kg (Guilhem et al., 2010). A three-dimensional relationship (torque-angle-load) was modelled using the method of least squares from the torque-angle relationship induced by each load. T_{WS} included the friction between the weight stack and the track bar, the cable and the pulleys, the pulleys and their bearings and the cable and the half-circle metal piece (Figure 2A).

The moment of inertia *{leg + resistance lever}* of the system J was assessed as the sum of each element's moment of inertia. The lower leg moment of inertia J_{leg} was calculated from anthropometric data (De Leva, 1996) as the sum of shank and foot moments of inertia, assuming a 90° angle of the ankle joint. The attachment moment of inertia J_{att} was determined using the Biodex System 3 Pro Research Toolkit. The system moved at six different constant accelerations (100, 200, 300, 400, 500 and 600°/s^2) and J_{att} was determined from the following equation:

$$T_{dyn} + T_{att} = J_{att} \cdot \ddot{\theta} \tag{6}$$

where T_{dyn} is the torque produced by the isokinetic dynamometer to accelerate the attachment (resistance lever and half-circle metal piece) (in Nm). J_{att} was estimated as the slope of the linear regression ($R^2 = 0.99$) between the sum of the torque ($T_{dyn} + T_{att}$) and the angular acceleration $\ddot{\theta}$.

Method B

Angular position θ of the resistance lever was computed from weight stack displacement d:

$$\theta = \theta_s - \frac{d}{R} \times \frac{180}{\pi} \tag{7}$$

where θ_s is the starting angular position i.e. 95°. θ was differentiated to obtain angular velocity $\dot{\theta}$ and differentiated twice to obtain angular acceleration $\ddot{\theta}$.

T_{att} was calculated as the cross product of the weight of the attachment W_{att} and its lever arm LA_{att}:

$$T_{att} = W_{att} \times LA_{att} \tag{8}$$

$$W_{att} = m_{att} \times g \tag{9}$$

$$\mathrm{LA}_{att} = \cos\theta \cdot X_{att} + \sin\theta \cdot Y_{att} \tag{10}$$

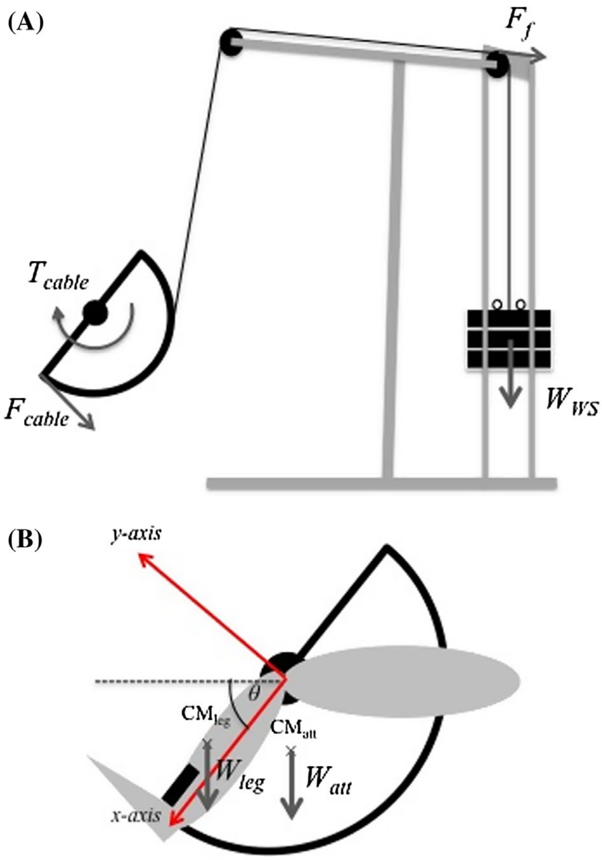

Figure 2. (A) Forces behind the resistive torque exerted by the cable (T_{cable}). For method A, T_{cable} was computed from the torque measured by the isokinetic dynamometer at a constant angular velocity and from the angular acceleration measured during the movement (Equation (4)). For method B, the force applied by the {*cable* + *weight stack*} system at the attachment point (F_{cable}) was multiplied by the radius of the half-circle metal component ($R = 0.395$ m) (Equation (16)). F_{cable} was obtained from the friction force applied on the system, the weight of the weight stack and the linear acceleration of the weight stack (Equation (14)). (B) Cartesian coordinate system, where the origin, *x*-axis and *y*-axis correspond with the centre of knee joint, the axis defined by the {*leg* + *resistance lever*} system and a perpendicular axis forwardly oriented. The position of CM_{leg}, the leg centre of mass, was estimated from anthropometrical data and used to assess the torque due to W_{leg}, the weight of the lower leg. The position of CM_{att}, the attachment centre of mass, was estimated experimentally and used to determine the torque due to W_{att}, the weight of the attachment. (C) Preliminary study for friction force F_f assessment (adapted from Bosco et al., 1995). Weights were hanging on the opposite extremity of the cable (W_H) to lift the weight stack (WS). Weight stack motion was measured using an optoelectronic motion capture system and used to compute $a1$ the linear acceleration of WS and W_H. Finally, F_f was computed from $a1$ and $a2$, the linear acceleration of WS and W_H and $W1$ and $W2$, the weight of WS and W_H.

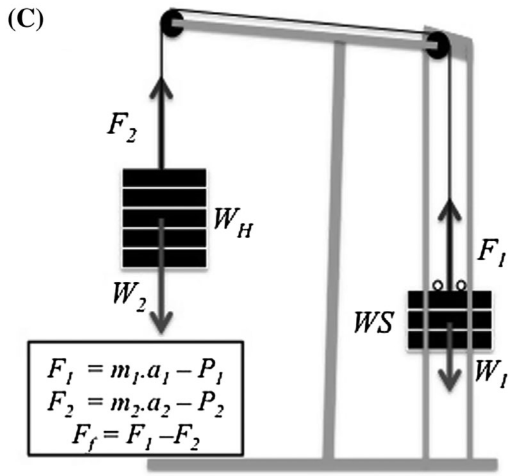

Figure 2. (*Continued*).

where m_{att} is the attachment mass (in kg); g, the gravitational constant (9.81 m/s^2); X_{att} and Y_{att} are the coordinates of the attachment centre of mass (in m) in the Cartesian coordinate system with origin corresponding with the centre of rotation (Figure 2B). The mass was measured using an electronic scale (Wedo Accurat 6000; Werner Dorsch, Dieburg, Germany). The two-dimensional centre of mass location was experimentally determined as the intersection of the lines of gravity obtained by suspending the attachment from three different locations. For manufactured strength-training devices, the attachment centre of mass could be provided by the manufacturer (Biscarini, 2012).

T_{leg} was computed as the cross product of the weight of the lower leg (considering shank and foot) W_{leg} and its lever arm LA_{leg}:

$$T_{leg} = W_{leg} \times LA_{leg} \tag{11}$$

$$W_{leg} = m_{leg} \times g \tag{12}$$

$$LA_{leg} = \cos\theta \cdot X_{leg} + \sin\theta \cdot Y_{leg} \tag{13}$$

where m_{leg} is the mass of the lower leg (in kg); X_{leg} and Y_{leg}, the coordinates of the leg centre of mass (in m) in the Cartesian coordinate system with origin corresponding with the resistance lever centre of rotation (Figure 2B). m_{leg} and LA_{leg} were estimated from anthropometric characteristics of the participant (De Leva, 1996; Figure 2B).

T_{cable} was assessed using the linear displacement of the weight stack. According to the Newton's Second law, the force applied on the *{cable + weight stack}* system is equal to the product of its mass m and its linear acceleration a. The cable was considered rigid and its mass was considered negligible in comparison to the mass of the weight stack in the following equations:

$$F_{cable} - F_f - W_{WS} = m_{WS} \cdot a_{WS} \tag{14}$$

$$F_{\text{cable}} = m_{\text{WS}} \cdot a_{\text{WS}} + F_f + W_{\text{WS}} \tag{15}$$

$$T_{\text{cable}} = (m_{\text{WS}} \cdot a_{\text{WS}} + F_f + W_{\text{WS}}) \times R \tag{16}$$

where F_{cable} is the cable force at the attachment point with the half-circle metal piece (in N) (Figure 2A); F_f, the overall friction force applied on weight stack, pulleys and cable (in N); W_{WS}, the weight of the weight stack (in N); m_{WS}, the mass of the weight stack (in kg) and a_{WS}, the linear acceleration of the weight stack (in m/s^2). a_{WS} was obtained by differentiating the weight stack displacement d. The assessment of F_f was conducted by modifying the method of Bosco et al. (1995) in order to include the frictions related to the pulleys (Figure 2C). Weights were hanging from the opposite extremities of the cable (W_H) in order to lift the weight stack (WS) along the track bar. The kinematics of WS was recorded using the motion capture system. F_f was computed using the fundamental principles of dynamics applied on $\{W_H\}$ and $\{WS\}$ systems:

$$F_1 = m_1 \cdot a_1 - W_1 \tag{17}$$

$$F_2 = m_2 \cdot a_2 - W_2 \tag{18}$$

$$F_f = F_2 - F_1 \tag{19}$$

where F_1 is the cable force acting on WS (in N); F_2, the cable force acting on W_H (in N); m_1 and m_2, the mass of WS and W_H (in kg); a_1 and a_2, the linear acceleration of WS and W_H with $a_2 = -a_1$ and W_1 and W_2, the weight of WS and W_H. The trials were performed using five different loads for WS (from 9.20 to 57.78 kg) and W_H (approximately 1.5 times greater than WS). For each trial, F_f was averaged over a 50-cm displacement of the weight stack, corresponding to a leg extension from 95° to 25°. Finally, F_f was expressed as a function of the mass of WS using a linear regression ($R^2 = 0.80$).

The moment of inertia of the *{leg + resistance lever}* system was assessed as the sum of each element's moment of inertia. The lower leg moment of inertia J_{leg} was calculated from anthropometric data (De Leva, 1996) as the sum of shank and foot moments of inertia, assuming a right angle at the ankle joint. The attachment moment of inertia J_{att} was estimated from method A and later was used in method B. For manufactured strength-training devices, J_{att} could be provided by the manufacturer (Biscarini, 2012).

Data collection and processing

The position θ of the resistance lever was manually calibrated on the day of testing using a spirit level to define the horizontal (0°) and vertical (90°) position. The opto-electronic motion capture system was calibrated according to the manufacturer's protocols. Anthropometric measurements, i.e. body mass, leg length, foot length and distance between the knee centre of rotation and the foot centre of mass, were recorded for each participant upon arrival. After a specific warm-up on the dynamometer, the individual 1-RM was determined as the maximal load (±1 kg) the participant could lift from 95° to 25°. Then, the participant was tested for isoinertial knee extensions using four different loads (30, 50, 70 and 90% of 1-RM) in a random order. For each condition, participants performed the first repetition at a submaximal intensity. Then, a second repetition was performed with the maximal intensity (i.e. maximal angular velocity for the given load). Both repetitions were considered for the analysis.

During the tests, the analogue mechanical signals provided by the isokinetic dynamometer (i.e. torque, angular position and angular velocity of the resistance lever) were sampled at 2,000 Hz (PowerLab 16/35, ADInstruments, Bella Vista, Australia). Two reflective markers were placed on the top of the weight stack and their three dimensional coordinates were recorded at 120 Hz using an opto-electronic motion capture system (Optitrack, NaturalPoint, OR, USA). Kinematic measurements of the weight stack were synchronised with mechanical measurements of the resistance lever.

Data were analysed using a custom script (MatLab, The Mathworks, Natick, USA). Mechanical and kinematic signals were smoothed using a recursive fourth-order Butterworth low-pass (10 Hz) filter. The midpoint between the two markers was used for the calculation of the weight stack kinematics. Mean and peak for torque and angular velocity were computed over a 70° range of motion (from 95° to 25°) with methods A and B. Torque-angle and angular velocity-angle relationships were determined by interpolating the torque and angular velocity signals for each degree of the 70° range of motion.

Statistical analysis

The level of agreement between methods A and B for mean angular velocity, peak angular velocity, mean torque and peak torque was assessed using Bland–Altman plots (Bland & Altman, 1986). Correlation (R^2) was also computed between the differences and the mean values to determine heteroscedasticity (when the magnitude of the differences depend on the mean values of the measured variables). R^2 values greater than 0.1 were considered heteroscedastic, while R^2 values between 0 and 0.1 were considered homoscedastic. Systematic bias and random error were then calculated. Mean percent difference ($M_{\mathrm{diff}} = \left[\frac{|X_{\mathrm{method1}} - X_{\mathrm{method2}}|}{\frac{X_{\mathrm{method1}} + X_{\mathrm{method2}}}{2}}\right] \times 100$) and effect sizes ($\mathrm{ES} = |X_{\mathrm{method2}} - X_{\mathrm{method1}}| \div \mathrm{SD}_{\mathrm{method1}}$) were used to assess the magnitude and spread of differences between both methods for all parameters (McMaster et al., 2014). ES calculations were included to express the mean difference between the two methods in standard deviation units such that an ES of 1 represents a difference equal to the standard deviation. Moreover, ES represent a standard unit for studies comparing performance measurement systems and calculation procedures and allows for comparison between these studies (Rhea, 2004).

Torque-angle and angular velocity-angle relationships obtained from both methods were compared using a Passing–Bablok regression (Bablok, Passing, Bender, & Schneider, 1988). The slope and the y-intercept of linear regressions with a 95% confidence interval (95% CI) were computed for each trial and averaged for the different levels of resistance. A significant difference between the two methods was found if '1.0' for the slope or '0' for the y-intercept were not included in the 95% CI.

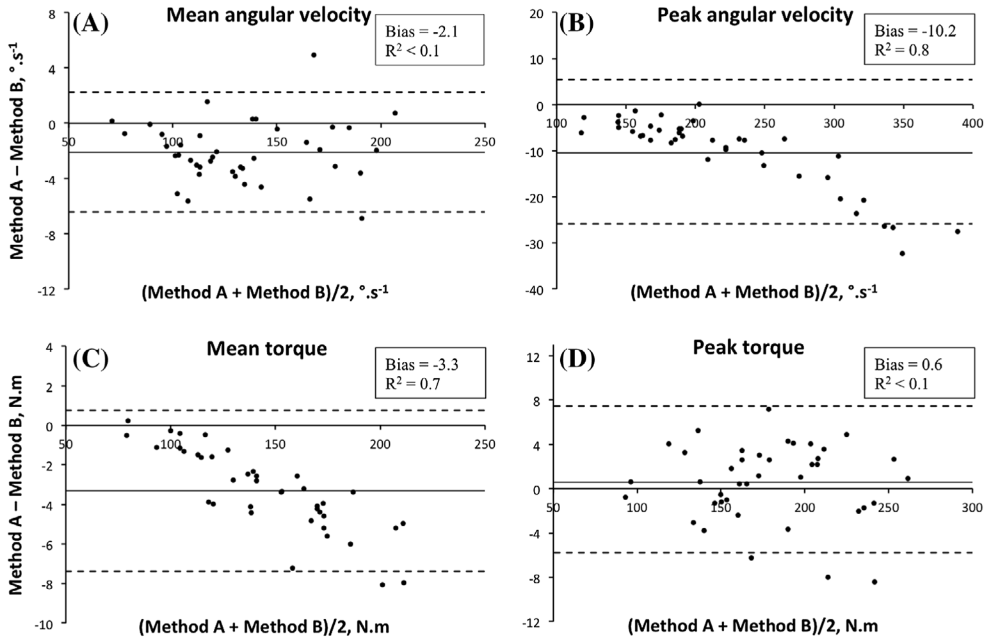

Figure 3. (A–D) Bland–Altman plots of differences (method A – method B) vs. mean of the two measures for mean angular velocity, peak angular velocity, mean torque and peak torque for the 40 trials. Upper and lower dashed lines represent the 95% limits of agreements, whereas the middle line symbolises the mean of the differences between method A and B (bias). To check the non-uniformity of the error, the correlation R^2 was provided. If $R^2 > 0.1$, data are considered as heteroscedastic where values ≤0.1 indicated homoscedastic data.

Table 2. Limits of agreement measured between methods A and B for mean and peak angular velocity and torque.

	Mean value (SD)		Mean percent difference (%)	Effect size	Hetero-sce-dasticity	Systematic bias	Random error
	A	B					
Mean angular velocity (°/s)	133 (31)	135 (31)	1.9	0.07	NO	−2.1	4.3
Peak angular velocity (°/s)	216 (61)	226 (68)	4.3	0.17	YES	−10.2	15.7
Mean torque (Nm)	144 (31)	147 (33)	2.1	0.11	YES	−3.3	4.1
Peak torque (Nm)	179 (32)	178 (32)	1.6	0.02	NO	0.6	6.9

Results

The Bland and Altman plots presented in Figure 3 indicated bias of −2°/s for mean angular velocity (95% CI = −6–2°/s; Figure 3A), −10°/s for peak angular velocity (95% CI = −26–5°/s; Figure 3B), −3.3 Nm for mean torque (95% CI = −7.4–0.8 Nm; Figure 3C) and 0.6 Nm for peak torque (95% CI = −6.3–7.5 Nm; Figure 3D). Mean torque and peak angular velocity were heteroscedastic ($R^2 < 0.1$), while peak torque ($R^2 = 0.7$) and mean angular velocity

(R^2 = 0.8) were homoscedastic. The mean per cent differences and effect sizes for each mechanical parameter assessed are presented in Table 2. Very low mean percent differences (between 1.6 and 4.3%) were found as confirmed by the low effect sizes (<0.15).

All conditions taken together, Passing–Bablok regressions did not show any difference between both methods for angular velocity (slope = 1.05, 95% CI = 0.96–1.11 and y-intercept = −1.91, 95% CI = −12.88–11.63; Table 3) and torque (slope = 0.90, 95% CI = 0.73–1.10 and y-intercept = 23.64, 95% CI = −5.66–47.23; Table 3). When considered separately, a significant difference was observed for torque at 30% of 1-RM only (slope = 0.87, 95% CI = 0.71–1.08 and y-intercept = 24.32, 95% CI = 0.50–40.88). No differences were found for any of the remaining other conditions (Table 3).

Discussion and implications

The objective of this study was to develop and compare two methods for mechanical analysis during single-joint isoinertial movement, using an isokinetic dynamometer-based approach (method A) and a weight stack kinematic-based approach (method B). We found high level of agreement between both methods for all the mechanical parameters analysed (M_{diff} < 5%), i.e. mean and peak angular velocity and torque. Mean angular velocity exhibited higher level of agreement than peak angular velocity, while the level of agreement between mean and peak torque was similar. Joint angular velocity-angle and torque-angle relationships did not show significant differences when computed from both methods, except for joint torque at 30% of 1-RM.

To our knowledge, this is the first study in which mechanical performance has been assessed from distinct input variables during single-joint exercise. Our results showed very low differences for peak and mean angular velocity computed using these methods (M_{diff} < 5% and ES < 0.2; Table 2). In a similar investigation focused on a multi-joint (squat jump) movement, Giroux, Rabita, Chollet, and Guilhem (2015) showed a bias value ranging from 8.4 to 9.7% for linear position transducer and accelerometer measurements compared to force plate measurements. Hori et al. (2007) concluded peak velocity during a loaded counter-movement jump to be over-estimated by 11.4% when compared linear position transducer to force plate. Lower differences observed in our study could be accounted for lower peak velocity reached during leg extension movement (i.e. 221°/s vs. 2.11 m/s). Indeed, our data indicate that the gap increased as the peak angular velocity increased (Figure 3B). The discrepancy could result from the inaccuracy related to the systems used for the measurements or to their calibration. The gap could also depend on the ability of the mechanical model used for method B to fit with the strength-training device behaviour. At high angular velocity, a slight difference could lead to high absolute errors. However, Passing–Bablok regressions (Table 3) did not reveal significant differences between angular velocity-angle relationships computed from both methods (Figure 4A).

Lower differences in torque compared to angular velocity resulted from the comparison of the two methods (M_{diff} < 2.1% and ES < 0.15; Table 2). Such observation and values were also reported in multi-joint movement (Giroux et al., 2015; Hori et al., 2007). For mean torque, absolute errors increased with an increase in the torque (Figure 3C). Passing–Bablok regressions (Table 3) did not reveal significant differences between method A and B for torque-angle relationships (Figure 4B) except for 30% of 1-RM. Discrepancies were particularly observed at the closest angles. Indeed, we observed a slight angle effect on the torque

Table 3. Slope and y-intercept of Passing–Bablok regression along with their corresponding 95% confident interval (95% CI[a]) for angular velocity-angle and torque-angle relationships.

		Slope		Y-intercept	
	Load (% of 1-RM)	Mean	95% CI	Mean	95% CI
Angular velocity (°/s)	30%	10.06	0.98–1.12	−30.84	−170.63 to 120.50
	50%	1.05	00.99–1.10	−2.20	−11.57 to 8.92
	70%	1.04	0.94–1.12	−0.65	−12.72 to 14.59
	90%	1.04	0.96–1.10	−0.94	−9.59 to 10.52
	All conditions	1.05	0.96–1.11	−1.91	−12.88 to 11.63
Torque (Nm)	30%	0.87	0.71–1.08	24.32	0.50 to 40.88
	50%	0.90	0.74–1.10	19.89	−5.32 to 40.00
	70%	0.90	0.72–1.14	23.27	−14.70 to 53.64
	90%	0.91	0.75–1.08	27.10	−3.09 to 54.39
	All conditions	0.90	0.73–1.10	23.64	−5.66 to 47.23

[a]95% CI defines the interval including 95% of the participants data.

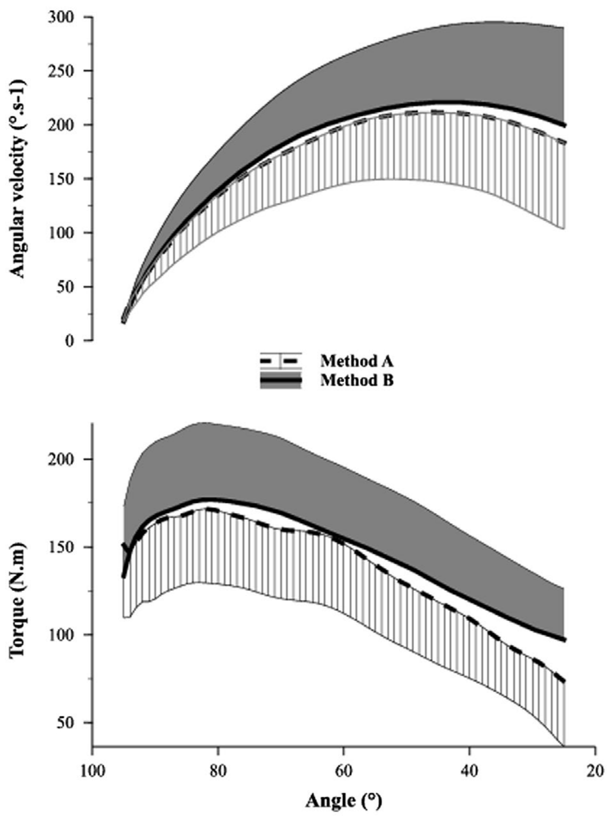

Figure 4. (A–B) Mean angular velocity-angle and torque-angle relationships computed from method A (isokinetic dynamometer; dotted line) and B (motion capture system; full line) all trials averaged. Angular velocity and torque were interpolated every degree from 95° to 25° (0°, resistance lever in horizontal position). The curves depict the values averaged across all trials.

that depends on the load applied. This is not considered in the method B and could partly explain the difference observed at closest angles.

Several limitations are acknowledged in the study. First, the differences between measurements obtained from both methods could be device-dependent. Nevertheless, the gap should be even lower on manufactured equipment owing to better fit between mechanical model and the strength-training device. Using light loads, limb high-deceleration phases can be observed at the end of the range of motion and result in a slack cable owing to higher weight stack inertia. This mechanism could alter the estimation of the knee angle from method B. For light loads, a special care should be given to weight stack kinematics and the range of motion calculation should be reduced to the acceleration phase. Finally, shear forces and misalignment between joint and dynamometer axes of rotation could affect the estimation of total joint torque and angle and limit the validity of the mechanical analysis (Tsaopoulos, Baltzopoulos, Richards, & Maganaris, 2011).

Conclusion

To our knowledge, our study is the first to develop a device and associated methodologies for maximal performance assessment of single-joint isoinertial movement. The results demonstrated the agreement between the two methods for torque and angular velocity assessment. According to the high level of agreement, both calculation procedures could be indifferently used to quantify the mechanical performance of a single-joint movement. This methodology offers sport coaches and scientists an alternative to the systematic use of isometric and isokinetic testing for single-joint movements. Specifically, it could be used to assess neuromuscular function of a specific muscle group, such as the quadriceps, defining torque-velocity or torque-angle relationships in ecological conditions. In this purpose, future studies are required to determine if isoinertial testing is more relevant than isometric and isokinetic testing. The development of new devices, more practical, is also necessary to promote the use of single-joint assessment in sport and rehabilitation field. Moreover, this technological development is important to perform a thorough comparison of iso-inertial and isokinetic resistance modalities, providing identical conditions to perform resistance-training exercises (i.e. body position, range of motion control and safety). Such researches can benefit to sport coaches, scientists and therapists that prescribed one or the other resistance modalities.

Abbreviation table

Notation	Definition	Units
1-RM	One-repetition maximum	kg
$\theta, \dot{\theta}, \ddot{\theta}$	Angular position, velocity and acceleration of the resistance lever	°, °/s, °/s^2
θ_s	Starting angular position	°
d, a	Linear displacement and acceleration of the weight stack	m, m/s^2
m_{att}	Mass of the attachment	kg
m_{leg}	Mass of the lower leg	
m_{WS}	Mass of the weight stack	
F_{cable}	Cable force at the attachment point with the half-metal circle piece	N
F_f	Friction force applied on weight stack and cable	

J	*{lower leg + attachment}* system moment of inertia	kg/m^2
J_{att}	Attachment moment of inertia	
J_{leg}	Lower leg moment of inertia	
J_{WS}	Weight stack moment of inertia	
LA_{att}	Lever arm of the attachment weight	m
LA_{leg}	Lever arm of the leg weight	
R	Radius of the half-circle metal piece	
T_{att}	Torque due to the weight of the attachment	Nm
T_{cable}	Torque exerted by the cable force at the attachment point with the half-metal circle piece	
T_{dyn}	Torque produced by the isokinetic dynamometer	
T_{joint}	Torque produced by the muscles crossing the knee joint	
T_{leg}	Torque due to the weight of the lower leg	
T_{WS}	Torque due to the weight of the *{cable + weight stack}* system	
W_{att}	Weight of the attachment	N
W_{leg}	Weight of the leg	
W_{WS}	Weight of the weight stack	
$[X_{att}, Y_{att}]$	Coordinates of the attachment centre of mass	m
$[X_{leg}, Y_{leg}]$	Coordinates of the leg centre of mass	

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