Accuracy of Biodex system 3 pro computerized dynamometer in passive mode

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A specific experimental design has been developed to determine the accuracy of the Biodex system 3 pro dynamometer in passive mode. Five cyclic stretching repetitions were imposed to an elastic rubber band at different velocities using the dynamometer, and the torque produced was measured using both the dynamometer and external force and position sensors. Velocity patterns performed by the dynamometer were also characterized and our results show that these patterns were reliable (ICC = 1.00). The torque measured with the dynamometer and the sensors were reliable (ICC = 1.00), although significant differences were observed between both methods. However, the measured torque standard error was velocity independent and was lower than 0.33 N m. Moreover, regressions between the two torque measurements were close to the axes-bisector ($r = 1.00$, slope: 1.01 ± 0.01, y-intercept: -0.36 ± 0.22 N m). Finally, our results showed decreases in torque during the five cycles, but these decreases were not due to the dynamometer. It can be concluded that the dynamometer performed valid torque measurements in passive mode, and was an accurate tool to determine passive mechanical properties of the musculo-articular system. However, some discrepancies between the programmed and the measured speed profiles have been observed when approaching the speed limit of the system.

Keywords: Instrumentation; Computerized dynamometer; Reliability; Validity; Stretching

1. Introduction

The use of computerized dynamometers has become popular for research, rehabilitation and training purposes. Some studies have validated their use to assess strength production capacities in different modes [1,2]. However, the reliability and validity of computerized dynamometers in different modes has yet to be demonstrated [3–6]. Reliability concerns the consistency between different measurements performed under similar conditions, and the measurement validity concerns the agreement between the observed value and the true value.

A recent study has shown that the Biodex system 3 pro dynamometer performs accurate angle and velocity measurements [4]. In this study, the accuracy of torque measurements was demonstrated, but only in a static (isometric) condition at a given angle. However, computerized dynamometers can also be used to assess musculo-articular mechanical properties using the torque-angle relationship obtained under a given range of motion by passively stretching the studied joint [7–11] for various preset velocities [12–18]. During passive movement, torque levels are lower than during active contractions. For example, at the knee joint, the maximal torque values reached during isometric knee extensions are about 300 N m for healthy young subjects [19], while it is only between 20 and 30 N m in passive conditions for similar subjects [8,11]. In addition, the magnitude of changes observed after different responses may be small values (e.g. about 3 N m after a static stretching protocol [11]). Thus, a slight error in measurement could be negligible during contraction, but might significantly influence parameters assessed in passive conditions.

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For instance, an energy loss at the level of the rotation axis of the dynamometer might introduce an error in the characterization of the passive mechanical properties of the musculo-articular complex. Therefore, the accuracy of passive torque measurements provided by computerized dynamometers has yet to be established. In addition, some authors have studied the effects of repeated stretching protocols on passive torque [8,10,11,20,21]. Since some significant strain could be present in the dynamometer during a stretching protocol, the dynamometer might contribute to the observed changes, and it is necessary to examine this possibility.

Drouin et al. [4] have shown that the Biodex system 3 pro preset in isokinetic mode is able to measure and accurately perform a movement at a constant velocity. In this contraction modality, the subject performs a maximal effort and the dynamometer regulates the movement at the preset velocity. The passive mode is quite different since, theoretically, the dynamometer produces the movement at a constant preset velocity. The reliability of velocity patterns performed under these conditions has not been assessed experimentally. Since resistance offered by the musculo-articular complex is angle [7,22] and velocity [12–18] dependent, it would be quite prejudicial to the results if the dynamometer did not perform identical patterns during cyclic stretching series or between two experimental sessions. Moreover, Rabita et al. [14] have shown that their dynamometer (Cybex) was not effectively able to reach preset velocities higher than $180^\circ\,s^{-1}$ over a range of motion of 40°. It means that acceleration capacities of computerized dynamometers limit their use to a velocity range, which is not yet understood.

Therefore, the aims of this study were (i) to determine the real velocity patterns imposed by the Biodex system 3 pro computerized dynamometer in passive conditions and to assess their reliability; (ii) to determine the reliability and the validity of torque measurements provided by the Biodex system 3 pro preset in passive mode at different velocities; (iii) to verify that the dynamometer does not contribute, even partially, to changes in passive torque during stretching.

2. Materials and methods

2.1. Experimental set-up

A specific experimental set-up designed for this study is depicted in Fig. 1. An elastic rubber band (16 mm diameter, Desiage, Thiers, France) was placed between the seat and the level arm of a Biodex system 3 pro computerized dynamometer (Biodex medical, Shirley, NY, USA) using two articulated systems (M and M′). The dynamometer measured angle (θ_{Biodex}), angular velocity (ω) and torque (T_{Biodex}). A position sensor (PT1, 1270 mm, error ±0.25% of rated capacity, Scaime, Annemasse, France) and a force transducer (Scaime, ZFA200 kg–3 mV/V, error ±0.03% of rated capacity, Annemasse, France) were placed between the seat of the Biodex system 3 pro and the elastic rubber band to measure its length (L) and the force produced in reaction to the stretch (F). L and F were used to recalculate the torque (T_{Sensors}) and the angle (θ_{Sensors}) during stretching. The experimental apparatus was designed in order (i) to start the stretch of the rubber at $\theta = -45^\circ$ ($\theta = 0^\circ$ corresponded to the level arm placed vertically) and (ii) to reach torque levels close to those usually observed during musculo-articular passive stretching performed *in vivo*. θ_{Biodex}, T_{Biodex}, F and L were sampled at 1000 Hz with an analogic/digital (A/D) converter (Spider8, HBM, Darmstadt, Germany) and stored on a computer (3.2 GHz, Dell, USA) using Catman software (HBM, Darmstadt, Germany).

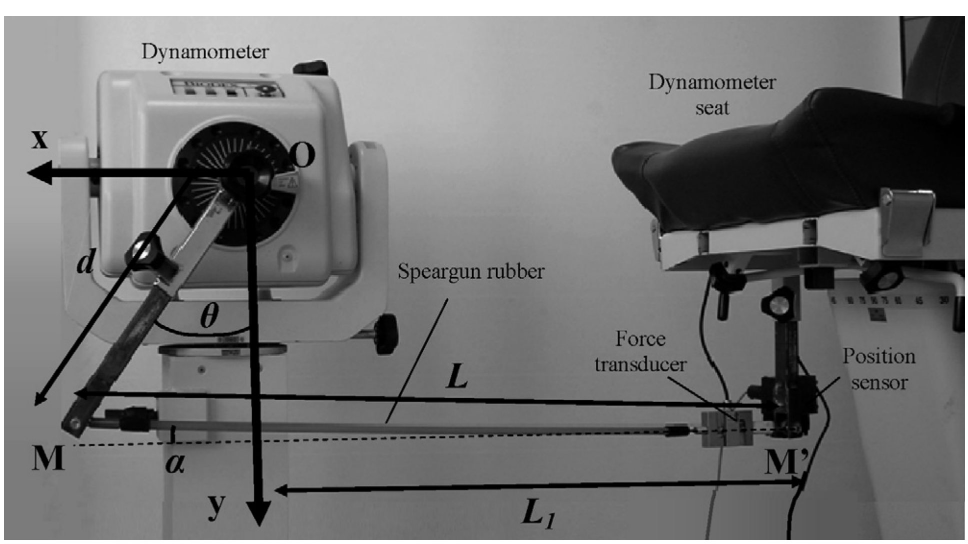

Fig. 1. Experimental set-up. A rubber was placed between the seat and the level arm ($d = 0.365$ m) of the Biodex system 3 pro using two articulated systems (M and M′). M′ was fixed while M moved with the level arm. L: length between M and M′ measured with the position sensor; L_1: constant length ($L_1 = 0.820$ m) between the vertical projection of the rotation axis and M′; θ: angle between the vertical axis (y) and the level arm, $-45^\circ < \theta < 45^\circ$, $\theta = 0^\circ$ corresponded to the level arm placed vertically; α: angle between the rubber and the horizontal axis (x).

2.2. Protocol

Five load/unload cycles were performed at preset angular velocities of 1, 2, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 75, 100, 125, 150, 175, 200, 225, 250, 275 and 300° s^{-1} from $\theta = -45°$ until $\theta = 45°$. This range of velocities was selected since it corresponds to the complete range of velocity that could be performed using the Biodex. For safety reasons, at velocities higher than 45° s^{-1}, the use of the system 3 pro software in passive mode implied that the first cycle was performed at a lower velocity than following cycles. Thus in this study, the system 3 research toolkit was used so that all passive cycles were performed at the same preset velocity. The protocol was repeated once on two separate days (D1 and D2).

2.3. Data processing

All of the data were processed using a standardized program using Matlab (The Mathworks, Natick, USA). Signals (θ_{Biodex}, T_{Biodex}, F and L) were calibrated using coefficients provided by manufacturers. Sensors were regularly checked in our laboratories to verify these coefficients. Signals were then filtered using a Butterworth second order low pass (10 Hz) filter. The filter was thereafter applied in a reverse direction of time to prevent the shift induced by the filter.

Velocity and acceleration patterns imposed by the dynamometer were subsequently analyzed. Acceleration, isokinetic and deceleration phases were assessed, and the range of each phase (in °) was determined for each cycle, at each velocity. Furthermore, the mean angular velocity during the cycle and the mean acceleration during the acceleration phase were calculated.

T_{Biodex} was corrected from the mass [23] and the inertia of the level arm. The angle was re-calculated using Eq. (1) solved using the symbolic math toolbox of Matlab ($\theta_{Sensors}$). $\theta_{Sensors}$, F and the dimensions of the apparatus (L_1 and d) were then used in Eq. (2) to calculate $T_{Sensors}$.

$$L_1 \sin\theta_{Sensors} - d\cos\theta_{Sensors} = \frac{L^2 - L_1^2 - 2d^2}{2d} \quad (1)$$

$$T_{Sensors} = dF\sin\theta_{Sensors}\sin\alpha + dF\cos\theta_{Sensors}\cos\alpha \quad (2)$$

where

$$\alpha = \arctan\left(\frac{d - d\cos\theta_{Sensors}}{L_1 + d\sin\theta_{Sensors}}\right)$$

T_{Biodex} and $T_{Sensors}$ were determined every 5° during cycles to assess T_{Biodex}–θ_{Biodex} and $T_{Sensors}$–$\theta_{Sensors}$ relationships. Finally, the potential elastic energy stored during loading (E, i.e. the area under load curve) and the potential elastic energy restituted (ER, i.e. the area under unload curve) were calculated using both Biodex and sensor signals. The dissipation coefficient (DC) was then determined as the energy dissipated normalized by the energy stored (Eq. (3) [11]).

$$DC = \frac{E - ER}{E} \quad (3)$$

E_{Biodex}, ER_{Biodex}, DC_{Biodex} and $E_{Sensors}$, $ER_{Sensors}$, $DC_{Sensors}$ were calculated using T_{Biodex}–θ_{Biodex} and $T_{Sensors}$–$\theta_{Sensors}$ relationships, respectively.

2.4. Experiment on an universal testing machine

A pilot experiment indicated a decrease in passive torque induced by cyclic stretching. In order to check that this change was not due, even partially, to the dynamometer, five cycles were performed at 400 mm min^{-1} with the same elastic rubber band placed on a universal testing machine that was calibrated to determine mechanical properties of materials (Zwick®, Ulm, Germany). The velocity 400 mm min^{-1} corresponds approximately to the lower lengthening velocity observed with the Biodex system 3 pro in our study (at 1° s^{-1}). However, because of a limitation of the linear machine, the range of stretch was preset at 320 mm, while the lengthening on the Biodex system 3 pro was about 500 mm. Force-lengthening relationships were analyzed by the same methods as that analyzed for torque-angle relationships.

2.5. Statistical analysis

Trial-to-trial reproducibility (between the five cycles performed at D1) and day-to-day reproducibility (between the first cycles performed at D1 and D2) were evaluated for the mean velocity, the mean acceleration, and the range of isokinetic plateau using the intraclass correlation coefficients (ICC), the standard error of measurement (SEM) and the coefficient of variation (CV) [4,24]. Day-to-day reproducibility of T_{Biodex} and $T_{Sensors}$ measurements was also assessed using ICC, SEM and CV.

To determine the validity of T_{Biodex}, a linear regression between T_{Biodex} and $T_{Sensors}$ was first performed at each velocity tested. The Bravais–Pearson correlation coefficient (r), slope and y-intercept of the linear regression, SEM and CV were then calculated [24]. The power of this method to assess the validity of a measurement is still discussed in the literature [3,6,25–27]. Thus, a Passing–Bablok regression [28,29] was also performed using Medcalc Software (version 9.1.0.1, Mariakerke, Belgium). This method determines the slope and the y-intercept of linear regressions with a 95% confidence interval (95% CI). A significant difference between the two measurements is found if "1.0" for the slope and/or "O" for the y-intercept are not included in the 95% CI.

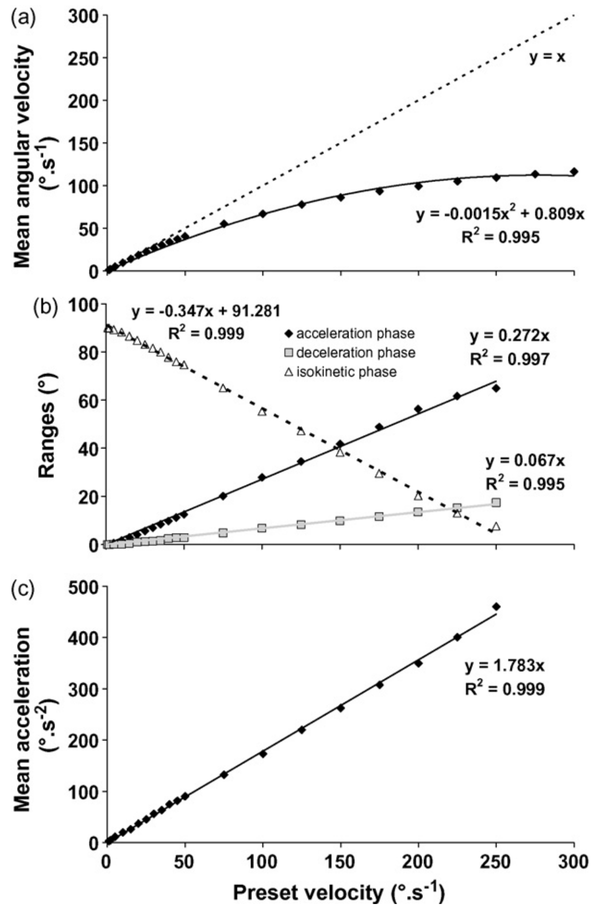

Fig. 2. (a) Mean velocity over the full range of motion during the cycle, (b) amplitudes of acceleration (⧫), deceleration (▢) and isokinetic (△) phases and (c) mean acceleration during the acceleration phase as functions of the preset velocity.

3. Results

3.1. Angular velocity and acceleration patterns

The dynamometer was not able to reach the preset angular velocities in the passive condition for 275 and 300° s^{-1} for the range of motion used in this study (90°). Thus, analyses of velocity and acceleration patterns were performed for the range of velocity spanning 1–250° s^{-1}. Fig. 2A shows that the averaged velocity on the whole range of motion was not linearly related to the preset velocity. For instance, for a preset velocity of 250° s^{-1}, the mean velocity was about 109° s^{-1}. Ranges of acceleration and deceleration phases increased linearly with the preset velocity, but the range of the deceleration phase was always lower than the acceleration phase (Fig. 2B). As a result, the range of the isokinetic plateau decreased linearly with the velocity. Fig. 2C shows that the mean acceleration during the acceleration phase increased in a linear way with the preset velocity. Finally, reliability analyses show near perfect trial-to-trial and day-to-day reproducibility for both mean velocity (trial-to-trial: ICC = 1.00, SEM = 0.26° s^{-1}, CV = 0.3%; day-to-day: ICC = 1.00, SEM = 0.20° s^{-1}, CV = 0.7%), mean acceleration (trial-to-trial: ICC = 1.00, SEM = 0.96° s^{-2}, CV = 2.2%; day-to-day: ICC = 1.00, SEM = 1.46° s^{-2}, CV = 3.6%) and range of isokinetic phase (trial-to-trial: ICC = 1.00, SEM = 0.11° s^{-2}, CV = 0.7%; day-to-day: ICC = 1.00, SEM = 0.29° s^{-2}, CV = 0.7%).

3.2. Reliability and validity of torque measurements

ICC, SEM and CV for the reliability of torque measurements are shown in Table 1. The results demonstrate an excellent reliability with ICC equal to 1.00 and SEM lower than 0.76 N m for both T_{Biodex} and T_{Sensors}. CV values were higher than 2% (2.01–12.83%). T_{Biodex}–θ_{Biodex} and T_{Sensors}–θ_{Sensors} relationships obtained at each velocity indicate the good agreement between T_{Biodex} and T_{Sensors}.

Results of analyses regarding the validity of torque measurements are shown in Table 2. Since *y*-intercepts were slightly lower than 0 and slopes were slightly higher than 1.0, Passing–Bablok regressions show significant differences between the two measurements. SEM and CV were small (less than 0.33 N m and 6.53%), and were not altered with velocity. Finally, the shapes of relationships between *E*, DC and mean angular velocity were very similar for both calculation methods (Fig. 3).

3.3. Effects of cycles

For all velocities used in this study (1–300° s^{-1}), the parameters E_{Biodex}, E_{Sensors}, DC_{Biodex} and DC_{Sensors} showed a decreased value after the first cycle. Typical examples of changes during the five cycles in E_{Biodex}, E_{Sensors} and DC_{Biodex}, DC_{Sensors} are reported in Fig. 4. Very similar changes were found using the two calculation methods for E (E_{Biodex}: −4.5 ± 1.4%, range: 1.5–6.5%; E_{Sensors}: −4.6 ± 1.7%, range: 0.5–7.5%) and DC (DC_{Biodex}: −22.0 ± 2.1%, range: 14.7–24.3%; DC_{Sensors}: −25.3 ± 5.8%, range: 14.7–34.9%).

E and DC were also lower during the five cycles performed using the universal testing machine (Fig. 5). E was about 21.6 and 21.3 J for the first and the fifth cycles, respectively. In addition, the decrease in DC was about 23.9%.

4. Discussion

Computerized dynamometers have often been used in passive mode to assess passive musculo-articular properties [7–18]. However, to our knowledge, the accuracy of the measurements provided by dynamometers under these conditions has not been demonstrated. Consequently, a specific experimental device has been developed to determine the accuracy of Biodex system 3 pro utilization in passive mode. Results of the present study showed that velocity patterns performed by the dynamometer were reliable and equations provided in

Table 1
Day-to-day reliability of torque measurements performed using the Biodex system 3 pro (T_{Biodex}) and sensors ($T_{Sensors}$) as a function of the preset velocity

Velocity (° s^{-1})	T_{Biodex}			$T_{Sensors}$		
	ICC[a]	SEM[b] (N m)	CV[c] (%)	ICC[a]	SEM[b] (N m)	CV[c] (%)
1	1.00	0.26	4.6	1.00	0.50	3.9
2	1.00	0.23	8.0	1.00	0.56	4.6
5	1.00	0.28	2.9	1.00	0.40	3.7
10	1.00	0.23	11.3	1.00	0.32	7.3
15	1.00	0.22	6.6	1.00	0.32	2.1
20	1.00	0.60	4.3	1.00	0.29	3.2
25	1.00	0.28	2.7	1.00	0.26	2.1
30	1.00	0.27	2.3	1.00	0.35	3.1
35	1.00	0.31	2.8	1.00	0.36	3.6
40	1.00	0.16	2.6	1.00	0.40	3.4
45	1.00	0.34	2.1	1.00	0.34	2.5
50	1.00	0.16	1.3	1.00	0.28	4.1
75	1.00	0.36	5.9	1.00	0.41	4.0
100	1.00	0.42	1.8	1.00	0.40	2.7
125	1.00	0.29	3.2	1.00	0.46	3.0
150	1.00	0.39	12.8	1.00	0.60	2.9
175	1.00	0.44	5.7	1.00	0.48	2.0
200	1.00	0.61	3.6	1.00	0.45	2.3
225	1.00	0.66	4.5	1.00	0.65	3.7
250	1.00	0.66	4.5	1.00	0.66	2.3
275	1.00	0.67	2.4	1.00	0.69	3.7
300	1.00	0.67	3.8	1.00	0.76	2.8

[a] Interclass correlation coefficient.
[b] Standard error in measurement.
[c] Coefficient of variation.

Table 2
Validity of torque measurements provided by the Biodex system 3 pro as a function of the preset velocity

Velocity (° s^{-1})	Linear regression [24]					Passing–Bablok regression [28]			
	r[a]	Slope[b]	y-Intercept[c]	SEM[d] (N m)	CV[e] (%)	Slope[b]	Slope[b] (95% CI)[f]	y-Intercept[c]	y-Intercept[c] (95% CI)[f]
1	1.00	1.03	−0.10	0.31	1.5	1.02	1.01–1.04	−0.15	−0.54 to 0.09
2	1.00	1.02	−0.37	0.26	0.7	1.02	1.01–1.03	−0.35	−0.63 to −0.10
5	1.00	1.02	−0.07	0.23	3.1	1.01	1.01–1.03	−0.15	−0.45 to 0.11
10	1.00	1.02	−0.25	0.18	0.4	1.02	1.01–1.03	−0.34	−0.67 to −0.11
15	1.00	1.01	−0.04	0.19	1.0	1.02	1.01–1.02	−0.10	−0.21 to 0.08
20	1.00	1.02	−0.47	0.19	0.5	1.02	1.01–1.03	−0.53	−0.87 to −0.26
25	1.00	1.01	−0.64	0.24	1.0	1.02	1.01–1.04	−1.00	−1.38 to −0.64
30	1.00	1.01	−0.32	0.14	0.4	1.03	1.02–1.03	−0.43	−0.63 to −0.13
35	1.00	1.01	−0.75	0.24	6.5	1.02	1.01–1.03	−1.21	−1.25 to −0.94
40	1.00	1.02	−0.56	0.24	0.9	1.02	1.01–1.04	−0.94	−1.13 to 0.64
45	1.00	1.01	−0.42	0.24	0.4	1.02	1.01–1.03	−0.69	−1.39 to −0.39
50	1.00	1.01	−0.48	0.23	0.7	1.02	1.01–1.04	−0.75	−1.52 to −0.44
75	1.00	1.01	−0.40	0.25	0.9	1.02	1.01–1.04	−0.65	−0.97 to −0.30
100	1.00	1.01	−0.41	0.23	0.5	1.02	1.02–1.03	−0.62	−0.43 to −0.41
125	1.00	1.01	−0.07	0.21	1.7	1.01	1.01–1.03	−0.15	−0.94 to 0.05
150	1.00	1.01	−0.42	0.26	0.8	1.02	1.01–1.03	−0.62	−0.61 to −0.31
175	1.00	1.01	−0.27	0.15	0.5	1.01	1.01–1.02	−0.36	−0.48 to −0.21
200	1.00	1.01	−0.07	0.17	1.3	1.02	1.01–1.03	−0.25	−0.34 to 0.09
225	1.00	1.01	−0.05	0.13	0.8	1.01	1.01–1.02	−0.14	−1.12 to 0.03
250	1.00	1.01	−0.55	0.21	1.1	1.01	1.00–1.02	−0.75	−0.87 to −0.49
275	1.00	1.01	−0.38	0.20	0.3	1.01	1.01–1.02	−0.65	−1.12 to −0.28
300	1.00	1.00	−0.77	0.33	1.3	1.01	0.99–1.02	−1.05	−1.59 to −0.60

[a] Bravais–Pearson correlation coefficient.
[b] Slope of linear regressions.
[c] y-Intercept of linear regressions.
[d] Standard error in measurement.
[e] Coefficient of variation.
[f] 95% confidence interval (lower to upper bound).

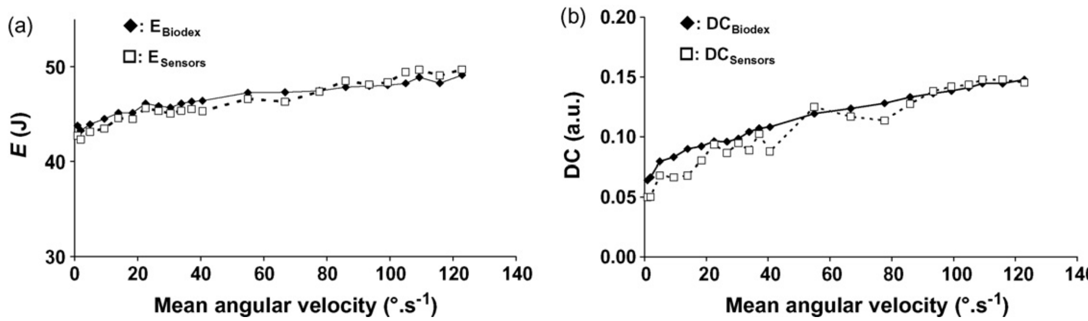

Fig. 3. (a) Potential elastic energy stored during the loading determined using the Biodex system 3 pro (E_{Biodex}, ⧫) and sensors (E_{Sensors}, □); (b) dissipation coefficient (DC) determined using the Biodex system 3 pro (DC_{Biodex}, ⧫) and sensors (DC_{Sensors}, □) as functions of the mean angular velocity during the cycle.

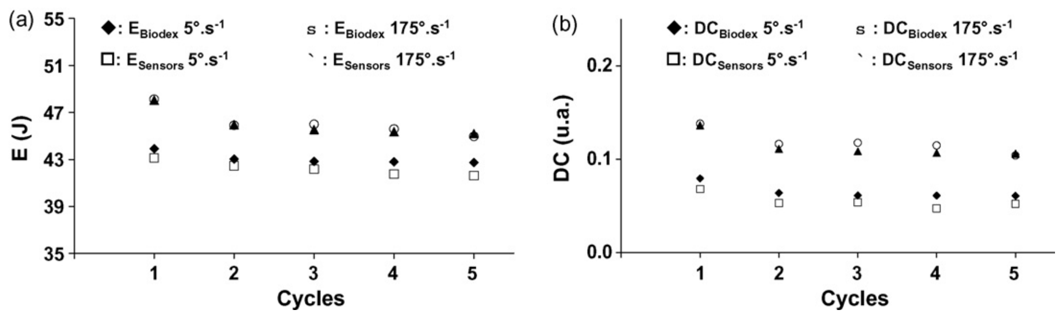

Fig. 4. Typical changes during the five cycles in (a) potential elastic energy stored during the loading determined using the Biodex system 3 pro (E_{Biodex}) and sensors (E_{Sensors}); (b) dissipation coefficient determined using the Biodex system 3 pro (DC_{Biodex}) and sensors (DC_{Sensors}). ⧫: calculated using the Biodex system 3 pro at $5^\circ\ s^{-1}$; ▲: calculated using the Biodex system 3 pro at $175^\circ\ s^{-1}$; □: calculated using sensors at $5^\circ\ s^{-1}$; ◯: calculated using sensors at $175^\circ\ s^{-1}$.

Fig. 2 could be used to determine ranges of the isokinetic phase as a function of the preset velocity. The torque measured with both the Biodex system 3 pro and the sensors was reliable. Although significant differences were observed between both methods, the measured torque standard error was lower than 0.33 N m. Finally, our results demonstrated that the passive torque decreases during the five cycles.

4.1. Angular velocity and acceleration patterns

Our results confirmed that the dynamometer preset in passive mode performed reproducible velocity patterns. Nevertheless, substantial acceleration and deceleration phases were found, and these phases must be taken into consideration by correcting the passive torque from the segment inertia. Moreover, for the highest velocities tested in our study (275 and $300^\circ\ s^{-1}$), the dynamometer was not able to reach preset velocities on the range of motion (90°) required. Equations depicted in Fig. 2 could be used to assess ranges of acceleration and deceleration phases, and to estimate the isokinetic plateau range as a function of the preset velocities. A range of motion of 90° was used in the present study, where in some clinical instances this range would not be employed as practical (e.g. for the ankle). However, we have verified that the ranges of acceleration and deceleration phases did not depend on the preset range of motion. For instance, the isokinetic plateau occurred at 39° using a preset range of 90° (calculated using the regression equation of Fig. 2), and would be about 19° if the preset range of motion were only 70°. Therefore, equation regressions of Fig. 2 could be used to

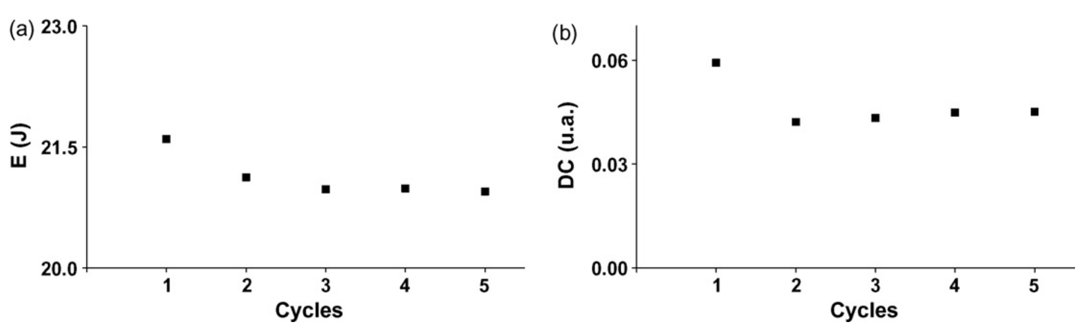

Fig. 5. Five cycles performed using the linear electromechanical machine. (a) Changes in potential elastic energy stored during the loading (E) and (b) changes in dissipation coefficient (DC).

calculate ranges of acceleration, deceleration and isokinetic phases whatever the range of motion under consideration.

Rabita et al. [14] have already shown that the Cybex computerized dynamometer used in passive mode was not able to reach $180^\circ\,s^{-1}$ on a 40° range of motion. In addition, these authors have reported a 3.6° isokinetic phase at $120^\circ\,s^{-1}$. At $120^\circ\,s^{-1}$, estimated acceleration and deceleration phases in our study were about 32.6° and 8.0°, respectively. Thus, the Biodex system 3 pro would not be able to reach $120^\circ\,s^{-1}$ on a 40° range of motion. Fig. 2C shows that the acceleration produced by the dynamometer increases linearly with the preset velocity, indicating that, even using the research toolkit, acceleration abilities of the dynamometer were not fully utilized to perform passive movements. It was probably still restrained for safety reasons. It would be a valuable to free it from these limitations in order to decrease ranges of acceleration phase, and increase the maximal velocity reached by the dynamometer.

4.2. Reliability and validity of torque measurements

Excellent day-to-day reproducibility of passive torque measurements provided by both Biodex system 3 pro and sensors were reported in Table 1. Despite low SEM (less than 0.36 N m), some values of CV were higher than 10% (Tables 1 and 2), especially at the beginning of the range of motion. In fact, at these angles, very low torque values were measured, which could largely explain higher CV values.

Passing–Bablok regressions (Table 2) showed that significant differences were found between T_{Biodex} and T_{Sensors}. Slopes and y-intercepts of Passing–Bablok regressions indicated that, in comparison to T_{Sensors}, T_{Biodex} was slightly underestimated at the beginning of the range of motion, and was slightly overestimated at the end of this range. Nevertheless, all linear regressions between T_{Sensors} and T_{Biodex} were near perfect ($r = 1$) and very close to the axis-bisector with SEM always lower than 0.33 N m. In addition, relationships between E_{Biodex}, E_{Sensors} and the velocity were very similar, indicating that there was no velocity dependent error in torque measurements. Moreover, DC_{Biodex} and DC_{Sensors} were very close showing that the Biodex system 3 pro determined the true dissipation of energy during the loading/unloading of the elastic rubber band. Consequently, our results demonstrated that the Biodex system 3 pro performed reliable and valid torque measurements during passive stretching at different velocities. This tool would be suitable to perform clinical studies, for instance, to assess the effects of ageing [12] or spasticity [13–18] on passive musculo-articular properties determined at different angular velocities.

4.3. Effects of cycles

Concomitant changes in E_{Biodex}, E_{Sensors} and DC_{Biodex}, DC_{Sensors} during cycles (Fig. 4) seemed to indicate that the decrease in passive torque induced by cyclic stretching was not influenced by the dynamometer, but reveals the actual capability of the elastic rubber band. To confirm this hypothesis, five cycles were performed with the same elastic rubber band placed on a universal testing machine calibrated to determine mechanical properties of materials. The results of this experiment (Fig. 5) showed that E and DC changes during the five cycles were similar to those observed in Fig. 4. For instance, changes in DC were close during the two experiments (Biodex system 3 pro: −17.8%; linear machine: −23.9%). Moreover, it is notable that the mean DC value obtained on the linear machine (averaged for the five cycles: 0.047) was similar to that determined with the Biodex system 3 pro (averaged for the five cycles at $1^\circ\,s^{-1}$: 0.053). These results confirmed that changes during cycles could not be influenced by the Biodex system 3 pro itself, but only reflected the actual mechanical properties of the tested system. Indeed, strain softening was originally shown to be a property of rubber called the Mullins effect [30].

4.4. Conclusion and perspectives

Velocity patterns imposed by the Biodex system 3 pro presets in passive mode were characterized in our study, and our results show that these patterns are reproducible. In addition, using a specific design, it has been demonstrated that passive torque measurements provided by the Biodex system 3 pro dynamometer are reliable and valid independently from the preset velocity. Finally, the dynamometer did not influence the observed changes in passive torque during cycles. Consequently, our results verified that the Biodex system 3 pro was an accurate tool to determine passive mechanical properties of the musculo-articular system, and the effects of stretching on these properties. In mechanical engineering, standards (ISO) are defined for use of standardized experimental devices to determine the mechanical properties of a material. It could be noticed that there are no such standards to determine mechanical properties of a musculo-articular complex *in vivo*, and the methodology used in this study could contribute to this necessary standardization.

5. Conflict of interest

No conflict of interest.

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References

[1] Pincivero DM, Lephart SM, Karunakara RA. Reliability and precision of isokinetic strength and muscular endurance for the quadriceps and hamstrings. Int J Sports Med 1997;18:113–7.

[2] Taylor NA, Sanders RH, Howick EI, Stanley SN. Static and dynamic assessment of the Biodex dynamometer. Eur J Appl Physiol Occup Physiol 1991;62:180–8.
[3] Atkinson G, Nevill AM. Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. Sports Med 1998;26:217–38.
[4] Drouin JM, Valovich-mcLeod TC, Shultz SJ, Gansneder BM, Perrin DH. Reliability and validity of the Biodex system 3 pro isokinetic dynamometer velocity, torque and position measurements. Eur J Appl Physiol 2004;91:22–9.
[5] Hopkins WG, Schabort EJ, Hawley JA. Reliability of power in physical performance tests. Sports Med 2001;31:211–34.
[6] Journois D. Concordance between two variables: graphical approach (Bland and Altman's method). Rev Mal Respir 2004;21:127–30.
[7] Gajdosik RL. Passive extensibility of skeletal muscle: review of the literature with clinical implications. Clin Biomech 2001;16:87–101.
[8] Magnusson SP, Aagard P, Simonsen E, Bojsen-Moller F. A biomechanical evaluation of cyclic and static stretch in human skeletal muscle. Int J Sports Med 1998;19:310–6.
[9] McNair PJ, Portero P. Using isokinetic dynamometers for measurements associated with tissue extensibility. Iso Exerc Sci 2005;13:53–6.
[10] Nordez A, Cornu C, McNair P. Acute effects of static stretching on passive stiffness of the hamstring muscles calculated using different mathematical models. Clin Biomech 2006;21:755–60.
[11] Nordez A, McNair PJ, Casari P, Cornu C. Acute changes in hamstrings musculo-articular dissipative properties induced by cyclic and static stretching. Int J Sports Med, in press.
[12] Gajdosik RL, Vander Linden DW, McNair PJ, Riggin TJ, Albertson JS, Mattick DJ, et al. Viscoelastic properties of short calf muscle-tendon units of older women: effects of slow and fast passive dorsiflexion stretches in vivo. Eur J Appl Physiol 2005;95:131–9.
[13] Lamontagne A, Malouin F, Richards CL, Dumas F. Impaired viscoelastic behavior of spastic plantarflexors during passive stretch at different velocities. Clin Biomech 1997;12:508–15.
[14] Rabita G, Dupont L, Thevenon A, Lensel-Corbeil G, Pérot C, Vanvelcenaher J. Quantitative assessement of the velocity-dependent increase in resistance to passive stretch in spastic platarflexors. Clin Biomech 2005;20:745–53.
[15] Engsberg JR, Olree KS, Ross SA, Park TS. Quantitative clinical measure of spasticity in children with cerebral palsy. Arch Phys Med Rehabil 1996;77:594–9.
[16] Engsberg JR, Ross SA, Olree KS, Park TS. Ankle spasticity and strength in children with spastic diplegic cerebral palsy. Dev Med Child Neurol 2000;42:42–7.
[17] Damiano DL, Quinlivan JM, Owen BF, Payne P, Nelson KC, Abel MF. What does the Ashworth scale really measure and are instrumented measures more valid and precise? Dev Med Child Neurol 2002;44:112–8.
[18] Ross SA, Engsberg JR. Relation between spasticity and strength in individuals with spastic diplegic cerebral palsy. Dev Med Child Neurol 2002;44:148–57.
[19] Aagaard P, Andersen JL, Dyhre-Poulsen P, Leffers AM, Wagner A, Magnusson SP, et al. A mechanism for increased contractile strength of human pennate muscle in response to strength training: changes in muscle architecture. J Physiol 2001;534:613–23.
[20] McNair PJ, Dombroski EW, Hewson DJ, Stanley SN. Stretching at the ankle joint: viscoelastic responses to holds and continuous passive motion. Med Sci Sports Exerc 2001;33:354–8.
[21] McNair PJ, Hewson DJ, Dombroski E, Stanley SN. Stiffness and passive peak force changes at the ankle joint: the effect of different joint angular velocities. Clin Biomech (Bristol, Avon) 2002;17:536–40.
[22] Magnusson SP. Passive properties of human skeletal muscle during stretch maneuvers. A review. Scand J Med Sci Sports 1998;8:65–77.
[23] Aagaard P, Simonsen EB, Trolle M, Bangsbo J, Klausen K. Isokinetic hamstring/quadriceps strength ratio: influence from joint angular velocity, gravity correction and contraction mode. Acta Physiol Scand 1995;154:421–7.
[24] Hopkins WG. Measures of reliability in sports medicine and science. Sports Med 2000;30:1–15.
[25] Atkinson G, Nevill A. Typical error versus limits of agreement. Sports Med 2000;30:375–81.
[26] Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. Lancet 1986;1:307–10.
[27] Bland JM, Altman DG. Comparing methods of measurement: why plotting difference against standard method is misleading. Lancet 1995;346:1085–7.
[28] Bablok W, Passing H, Bender R, Schneider B. A general regression procedure for method transformation. Application of linear regression procedures for method comparison studies in clinical chemistry, Part III. J Clin Chem Clin Biochem 1988;26:783–90.
[29] Fuhrman C, Chouaid C. Concordance between two variables: numerical approaches (qualitative observations—the kappa coefficient; quantitative measures. Rev Mal Respir 2004;21:123–5.
[30] Marckmann G, Verron E, Gornet L, Chagnon G, Charrier P, Fort P. A theory of network alteration for the Mullins effect. J Mech Phys Solids 2002;50:2011–28.