Published in : Isokinetics and Exercise Science (2019), vol. 27, no.1, pp. 41-54
DOI: 10.3233/IES-176210
Status : Postprint (Author's version)

MEASURED AND DERIVED PARAMETERS OF ISOKINETIC FATIGABILITY OF KNEE MUSCLES: WHAT CAN WE APPLY, WHAT SHOULD WE NOT?

J. Paulus[a], L. Bosquet[b], B. Forthomme[a,c], A.-F. Donneau[d], V. Grémeaux[e] and J.-L. Croisier[a,c]

[a]*Department of Motricity Sciences and Physical Therapy and Rehabilitation, University of Liege, Liege, Belgium*
[b]*Faculty of Sport Sciences, University of Poitier, Poitiers, France*
[c]*Department of Physical Medicine and Sport Traumatology, University of Liege, Liege, Belgium*
[d]*Department Public Health Sciences, University of Liege, Liege, Belgium*
[e]*Pole Rehabilitation, University Hospital Center of Dijon, Dijon, France*

ABSTRACT

Background: Fatigability measured and derived parameters are commonly used in research and clinical contexts to characterize performance during isokinetic fatigue protocols. The fatigability measured parameters are the best repetition, the total and the partial sums while the fatigability derived parameters are ratios and formula-based parameters.

Objectives: To comprehensively evaluate the reproducibility of fatigability measured and derived parameter and to determine which of these is/are sufficiently interpretable for assessment of knee muscles.

Methods: Eighteen sedentary men underwent three isokinetic knee fatigability testing sessions with 7–10 days of rest between each session. Peak moment (PM) and maximal work (MW) were computed for each repetition and analyzed to calculate 54 measured and derived parameters. Relative (Intra-class Correlation Coefficients – ICC) and absolute (Coefficient of Variation of Method Error – CV_{ME}%, standard error of measurement – SEM and minimum detectable change – MDC) parameters of reproducibility were determined to assess the inter-session agreement.

Results: All fatigability measured parameters (save one) were associated with a high relative and absolute reproducibility for knee extensors (ICC $\geqslant$ 0.80; almost all SEM $\leqslant \frac{SD}{2}$; MDCs largely ranging 10–30%) and a high relative but weak absolute reproducibility for flexors (ICC $\geqslant$ 0.70; SEM $> \frac{SD}{2}$; MDCs ranging 35–95%). On the other hand, all knee extensor and flexor fatigability derived parameters were characterized by low relative and absolute reproducibility ($ICC_{extensors} < 0.70$ and $ICC_{flexors} < 0.50$; all SEM $> \frac{SD}{2}$; MDCs largely ranging 30–100%).

Conclusions: All fatigability measured parameters may be used for assessing knee extensors fatigue with either PM or MW; for assessing knee flexors, no measured parameters can be utilized. Above all, knee fatigability derived parameters, either PT- or MW-based, should not be used, for both the extensors and the flexors of the knee, due to clinically unacceptable reproducibility.

KEYWORDS: Reproducibility, fatigability parameter, measured and derived parameters, responsiveness, knee joint.

1. Introduction

Based on its reproducibility and sensitivity [1, 2] in research and clinical contexts [3], isokinetic testing has become a gold standard in muscular strength evaluations. Commonly, isokinetic devices are used to assess strength at various velocities by means of short duration testing. However, in some cases, the evaluation of muscle endurance to fatigue may be more specific than that of strength; for instance, in athletes who mainly use lactic anaerobic metabolism to perform or in patients with neuromuscular pathology [4, 5].

As defined by Bigland-Ritchie et al., fatigue refers to "any reduction in the capacity of the total neuromuscular system to generate force, regardless the force level deployed" [6, 7]. Generally, the knee fatigability protocol consists of a defined number of reciprocal maximal concentric contractions or in the largest number of repetitions in a given period of time, all performed at a prescribed velocity, e.g. $180°/s$ [8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20]. A great heterogeneity between protocols remains regarding the predefined number of repetitions or test duration [4, 9, 12, 15, 17, 21, 22, 23, 24, 25] despite the fact that Bosquet et al. [6] have shown that thirty reciprocal maximal concentric contractions appears to be the best compromise between reliability, specificity and interpretability of the data.

In the clinical context practitioners commonly use some fatigability derived parameters which, in some cases, are provided by the dynamometer's dedicated software. For instance, the Biodex software compares the first and the last third of repetitions in the set to obtain a percentage decline. The fatigability measured parameters are the best performance, the total and partials sums while the fatigability derived parameters are the quotient between the $n$last repetitions by the $x$first, between the total sum by the best, and so on; in other words, the fatigability derived parameters are the ratios and the formula-based parameters. Thus, the derived parameter is attractive by its theoretical ability to characterize the decrease in performance during the test. Many clinicians and researchers base respectively their analysis and possible implications in rehabilitation or training on these derived parameters. The literature provides a multitude of derived parameters [17, 18, 24, 26, 27, 28, 29, 30, 31, 32].

However, the question is still open on which isokinetic fatigability parameter(s) may be recommended for use in evaluating the knee muscles. The first step in this determination is to clarify their intra-dynamometer reproducibility. Although several studies had assessed the reproducibility of knee isokinetic fatigability protocols [6, 9, 12, 13, 14, 32, 33, 34, 35, 36, 37, 38, 39], to our knowledge, none has done so in terms of both the relative and the absolute reproducibility of the fatigability parameters. Therefore, the goal of our study was to evaluate, as comprehensively as possible, the intra-dynamometer reproducibility of fatigability measured and derived parameters so

Published in : Isokinetics and Exercise Science (2019), vol. 27, no.1, pp. 41-54
DOI: 10.3233/IES-176210
Status : Postprint (Author's version)

as to determine which have sufficient reproducibility for application in clinical and research environments.

2. Methods

2.1 SUBJECTS

Eighteen recreationally men, with no history of (major) knee injury, practicing less than two hours of physical activity per week and not involved in specific muscle training of the lower limbs were included in this study. Any drug or medication intake was an exclusion criterion. This study, approved by the Ethics Committee of the University and Faculty Hospital, was conducted in conformity with ethical standards and (inter) national laws [40] and with the Helsinki declaration of 1975, as revised in 2000. All subjects were informed about the protocol, submitted to a medical examination and signed an information and consent form. Age, size and body weight means $\pm$SD were 23.4 $\pm$2.4 years, 179 $\pm$8 cm and 71.0 $\pm$3.4 kg, respectively.

2.2 EXPERIMENTAL DESIGN

Three isokinetic testing sessions were carried out, with seven to ten days of rest between each session, for each subject under the supervision of a single physical therapist. To avoid possible effects of a residual fatigue due to recent exercises, subjects were asked to refrain from physical activity for forty-eight hours before each evaluation session. In order to standardize the testing session conditions, subjects were asked:

- to follow a stable sleep schedule in the three days before the sessions;
- not to eat any meal in the three hours preceding the sessions;
- not to drink coffee, tea or any other energy drink the day of the sessions.

2.3 EXERCISE TESTING

The evaluations were performed on a Biodex dynamometer (Biodex Medical Systems 3, Shirley, NY). This dynamometer has an excellent reliability with an ICC of 0.99 for position, peak moment and velocity [41]. We tested only the dominant leg, defined as kicking leg. The test position was in sitting, with the backrest raised at 85° to the horizontal. Proximal stabilization was provided by straps at the thigh, pelvis and shoulders. The knee axis of rotation was aligned with that of the dynamometer using the external condyle as an anatomical landmark. The press hold was positioned three centimeters above the external malleolus on the front side of the leg. The RoM was set to 100° with 0° corresponding to the maximum active extension. Gravity compensation was performed by the dynamometer's software.

Prior to testing, subjects were instructed to push up and pull down until the dynamometer stopped, in order to achieve a full RoM. To ensure familiarization and complete the set-up, the subjects were

Published in : Isokinetics and Exercise Science (2019), vol. 27, no.1, pp. 41-54
DOI: 10.3233/IES-176210
Status : Postprint (Author's version)

making submaximal but progressively intensified concentric contractions intensity at 120°/s [42]. After two minutes of rest, subjects had to perform three reciprocal concentric submaximal contractions at 180°/s.

In this study we used the same database as did Bosquet et al. [6] who studied the effects of lengthening the isokinetic evaluation of muscle endurance to fatigue. The subjects underwent the formal test, which consisted of 50 consecutive maximal reciprocal flexion-extension concentric contractions at 180°/s. Subjects were asked to push up and pull down as fast and hard as possible from the first repetition and during each subsequent repetition over the full RoM previously determined. To motivate the subjects to develop the highest capacity at each repetition they received verbal encouragement throughout the testing session [43]. Our analysis was performed on the first thirty repetitions of each of the three testing sessions performed by the subjects.

2.4 DATA ANALYSIS

Peak moment (PM in N·m) and Maximal Work (MW in J) were computed for each repetition and then analyzed to calculate 54 fatigability parameters (refer back to Table 1). The MW, although frequently neglected, has been included in our analyses due the differences in information provided by these two parameters: the PM represents the highest moment reading produced during a given contraction while the MW is the area under the moment curve [6, 44]. As reported by Manca et al. [45], a PM-based only analysis may induce an overestimation of the muscular moment output [46]. Therefore, several researchers [45, 47] have suggested using MW alongside PM, especially in the rehabilitation process [48] and in frail populations. This approach was adopted in this study. The normality of the distribution of the data was verified using the Shapiro-Wilk test. When this was violated, data were log-transformed (provided that the normality of the distribution of log-transformation is verified). Systematic bias, which refers to a general trend for measurements to be different in a particular direction when compared between repeated tests [49], was assessed with a general linear model for repeated measures ANOVA. The compound symmetry was checked by the Mauchley test. When the assumption of sphericity was not met, the significance of F-ratios was adjusted according to the Greenhouse-Geisser or Huynh-Feldt procedure (when the epsilon correction factor was respectively lower or higher than 0.75). The multiple pairwise comparisons between sessions were made with the Tukey's post-hoc test.

Table 1. Knee parameters

Fatigability measured parameters			
BR_1	$\Sigma[R11{:}R20]$	$\Sigma[R6{:}R10]$	$\Sigma[R21{:}R25]$
$\Sigma[R1{:}R30]$	$\Sigma[R21{:}R30]$	$\Sigma[R11{:}R15]$	$\Sigma[R26{:}R30]$
$\Sigma[R1{:}R10]$	$\Sigma[R1{:}R5]$	$\Sigma[R16{:}R20]$	
Fatigability derived parameters			
Quotient of the last n repetitions by the first n repetitions			

Published in : Isokinetics and Exercise Science (2019), vol. 27, no.1, pp. 41-54
DOI: 10.3233/IES-176210
Status : Postprint (Author's version)

$\frac{WR_1}{BR_1}$	$\frac{\overline{[R29:R30]}}{\overline{[R1:R2]}}$	$\frac{\overline{[R28:R30]}}{\overline{[R1:R3]}}$	$\log\frac{\overline{[R26:R30]}}{\overline{[R1:R5]}}$
$\log\frac{\overline{[R21:R30]}}{\overline{[R1:R10]}}$			
Quotient of the last n repetitions by the first y repetitions			
$\frac{\overline{[R29:R30]}}{\overline{[R1:R3]}}$	$\frac{\overline{[R29:R30]}}{\overline{[R1:R5]}}$	$\frac{\overline{[R29:R30]}}{\overline{[R1:R10]}}$	$\frac{\overline{[R28:R30]}}{\overline{[R1:R2]}}$
$\log\frac{\overline{[R28:R30]}}{\overline{[R1:R5]}}$	$\log\frac{\overline{[R28:R30]}}{\overline{[R1:R10]}}$	$\frac{\overline{[R26:R30]}}{\overline{[R1:R2]}}$	$\frac{\overline{[R26:R30]}}{\overline{[R1:R3]}}$
$\log\frac{\overline{[R26:R30]}}{\overline{[R1:R10]}}$	$\log\frac{\overline{[R21:R30]}}{\overline{[R1:R2]}}$	$\log\frac{\overline{[R21:R30]}}{\overline{[R1:R3]}}$	$\log\frac{\overline{[R21:R30]}}{\overline{[R1:R5]}}$
Quotient of n repetitions by the y best repetitions			
$\log\left[\frac{\Sigma[R1:R30]}{BR_1}\right]$	$\frac{\overline{[R29:R30]}}{BR_1}$	$\frac{\overline{[R28:R30]}}{BR_1}$	$\frac{\overline{[R26:R30]}}{BR_1}$
$\frac{\overline{[R21:R30]}}{BR_1}$	$\frac{\overline{[R29:R30]}}{\overline{[BR_1:BR_2]}}$	$\frac{\overline{[R29:R30]}}{\overline{[BR_1:BR_3]}}$	$\frac{\overline{[R29:R30]}}{\overline{[BR_2:BR_3]}}$
$\log\frac{\overline{[R28:R30]}}{\overline{[BR_1:BR_3]}}$	$\log\frac{\overline{[R28:R30]}}{\overline{[BR_2:BR_4]}}$	$\log\frac{\overline{[R26:R30]}}{\overline{[BR_1:BR_5]}}$	$\log\frac{\overline{[R26:R30]}}{\overline{[BR_2:BR_6]}}$
$\log\frac{\overline{[R21:R30]}}{\overline{[BR_1:BR_{10}]}}$	$\log\frac{\overline{[R21:R30]}}{\overline{[BR_2:BR_{11}]}}$		
Quotient of n repetitions by the y best consecutives repetitions			
$\frac{\overline{[R29:R30]}}{\overline{CBR_2}}$	$\log\frac{\overline{[R28:R30]}}{\overline{CBR_3}}$	$\log\frac{\overline{[R26:R30]}}{\overline{CBR_5}}$	$\log\frac{\overline{[R21:R30]}}{\overline{CBR_{10}}}$
$\log\frac{\overline{CWR_2}}{\overline{CBR_2}}$	$\log\frac{\overline{CWR_3}}{\overline{CBR_3}}$	$\log\frac{\overline{CWR_5}}{\overline{CBR_5}}$	$\log\frac{\overline{CWR_{10}}}{\overline{CBR_{10}}}$
Various others derived parameters			
$\frac{R_{29}}{R_2}$	$\frac{WR_2}{BR_2}$	$\frac{WR_2}{BR_1}$	$\frac{WR_1}{BR_2}$

Note: $BR_x = x^{\text{th}}$ Best Repetition; $WR_x = x^{\text{th}}$ Worst Repetition; $R_x = x^{\text{th}}$ repetition; $\Sigma[Rx:Ry]$ =cumulated performance from x^{th} to y^{th} repetition; $\overline{[Rx:Ry]}$average performance from x^{th} to y^{th} repetition; $\overline{[BR_x:BR_y]}$ =average performance from x^{th} better to y^{th} better repetition; $\overline{CBR_x}$ =average performance of best x consecutives repetitions; $\overline{CWR_x}$ =average performance of worst x consecutives repetitions.

Relative reproducibility was determined using the $ICC_{2,1}$ (single measures) which "represents the proportion of variance in a set of scores that is attributable to the true score variance" [50]. An ICC higher than 0.90 is considered excellent, between 0.70 and 0.89 as high and between 0.50 and 0.69

Published in : Isokinetics and Exercise Science (2019), vol. 27, no.1, pp. 41-54
DOI: 10.3233/IES-176210
Status : Postprint (Author's version)

as moderate [6, 51]. Currier [52] and Saenz et al. [33] have suggested that an ICC value higher than 0.80 is highly reliable and acceptable for clinical work. ICC is presented as value along with its 95% CI.

Absolute reproducibility was assessed using the Standard Error of the Mean (SEM), considered as expected trial-to-trial noise in the data [50]. The Minimum Detectable Change (MDC), based on SEM, which is defined as minimal amount of change outside of error that reflects true change by a subject between two evaluations, was also calculated. SEM and MDC are expressed in the unit (N·m, J or dimensionless quantities) of the parameter.

ICC (Eq. (2.4)), SEM (Eq. (2)) and MDC at the 95% confidence level (Eq. (3)) were computed from the table of a two-way analysis of variance (trials × subjects) with repeated measures, using the following equations [6, 50, 53]:

$$ICC = \frac{MS_S - MS_E}{MS_S + (K-1) * MS_E + \frac{k * (MS_T - MS_E)}{n}} \quad (1)$$

where MS_S = mean squared subjects, MS_E = mean squared error, MS_T = mean squared trials, n = number of subjects and k = number of trials.

$$SEM = \sqrt{MS_E + MS_T} \quad (2)$$

$$MDC = SEM * 1.96 * \sqrt{2} \quad (3)$$

Where SEM $\leqslant \frac{SD}{2}$ was taken as the criterion for acceptable precision [54, 55, 56, 57, 58, 59].

The absolute (Eq. (4)) and relative (Eq. (5)) variability are calculated using the following equations:

$$V_{\text{abs.n}} = |R_{n+1} - R_n| \quad (4)$$

$$V_{\text{rel.n}} = \left|\frac{R_{n+1} - R_n}{R_{n+1}}\right| \quad (5)$$

where R_n = the value of the n^{th} repetition with $n \in \mathbb{N}, 1 \leqslant n \leqslant 29$.

The Coefficient of Variation of Method Error (CV_{ME}), reported as a percentage, is defined by the following equation (Eq. (6)) [49, 73]:

$$CV_{ME}\% \frac{SEM}{\text{mean of parameter}} * 100$$

Published in : Isokinetics and Exercise Science (2019), vol. 27, no.1, pp. 41-54
DOI: 10.3233/IES-176210
Status : Postprint (Author's version)

(6)

Where SEM is defined previously (Eq. (2)) and where *mean of parameter* is the mean value of the measured or derived parameter's value (from the three tests occasions).

The linear correlation between two variables was measured by the Pearson's r product-moment correlation coefficient (PCC) and linear regression analyses with coefficients of determination associated (r^2). Threshold values for PCC statistics were < 0.20, 0.20, 0.60 and 0.80 for weak, moderate, strong and very strong, respectively [60]. The PCC was calculated 1) between the progress of the testing session and the (absolute and relative) variability (separately for PM and MW) to explore the relation between fatigue induction and variability of the performance; 2) between the PM and the MW of repetition (separately for the extensors and the flexors) to determine if fatigue had a similar influence on these two parameters over the three sessions; 3) between the extensors and the flexors (separately for the PM and the MW) to determine if fatigue had a similar influence on these antagonistic muscle groups.

Statistical significance was set at the level of p-value < 0.05 for all analyses. All calculations were made with Statistica 10 (Statsofts, Tulsa, OK), MedCalc 13.3.3 (MedCalc Software, Ostend, Belgium) and Microsoft Excel 2016.

3. Results

The PM and MW mean values and standard deviation from the three testing sessions for the knee extensors and flexors are presented in Table 2.

Table 2. Knee mean value ±standard deviation for testing sessions 1–3

	Knee extensors					
	Session 1		**Session 2**		**Session 3**	
PM	114.5	±28 N·m	115.5	±27.9 N·m	115.9	±26.8 N·m
MW	136.2	±35.9 J	136.5	±35.6 J	137.7	±34.4 J
	Knee flexors					
	Session 1		**Session 2**		**Session 3**	
PM	60	±17.9 N·m	64.2	±17.5 N·m	64.3	±16.5 N·m
MW	74.3	±25.2 J	78.5	±24.2 J	79.5	±23.5 J

Published in : Isokinetics and Exercise Science (2019), vol. 27, no.1, pp. 41-54
DOI: 10.3233/IES-176210
Status : Postprint (Author's version)

Table 3. Absolute and relative variability mean value ± standard deviation, ICC, ICC CI 95%, CV, SEM and MDC for knee extensors and flexors

	Peak moment						Maximal work					
	Knee extensors											
	Mean ± SD (N·m)	ICC	ICC CI 95%	CV	SEM	MDC	Mean ± SD (J)	ICC	ICC CI 95%	CV	SEM	MDC
$\Sigma[V_{abs.1}:V_{abs.29}]$	138.5 ± 34.7	0.327	0.030/0.638	25.5%	35.3	70.7%	174.7 ± 36.0	0.150	−0.119/0.492	30.9%	53.9	85.5%
$\Sigma[V_{rel.1}:V_{rel.29}]$	1.29 ± 0.40	0.278	−0.014/0.600	42.6%	0.55	117.5%	1.38 ± 0.36	0.210	−0.071/0.544	44.2%	0.61	123.3%
	Knee flexors											
	Mean ± SD (N·m)	ICC	ICC CI 95%	CV	SEM	MDC	Mean ± SD (J)	ICC	ICC CI 95%	CV	SEM	MDC
$\Sigma[V_{abs.1}:V_{abs.29}]$	109.6 ± 28.3	0.303	0.008/0.620	24.2%	26.5	67.1%	136.1 ± 31.6	0.327	0.030/0.637	22.5%	30.6	62.4%
$\Sigma[V_{rel.1}:V_{rel.29}]$	1.97 ± 0.59	0.344	0.046/0.650	40.6%	0.80	112.4%	2.03 ± 0.63	0.496	0.202/0.752	32.5%	0.66	90.5%

Table 4. Knee extensors parameters Peak moment & Maximal Work mean value ± standard deviation, ICC, ICC CI 95%, CV, SEM (expressed in N·m for PM and in J for MW) and MDC

	Peak moment						Maximal work					
	Mean ± SD (N·m)	ICC	ICC CI 95%	CV	SEM	MDC	Mean ± SD (J)	ICC	ICC CI 95%	CV	SEM	MDC
Fatigability measured parameters												
BR_1	161.2 ± 20.5	0.920	0.832/0.968	3.3%	8.2	14.1%	193.4 ± 26.9	0.936	0.862/0.974	5.3%	10.3	14.8%
$\Sigma[R1:R30]$	3464.4 ± 423.6	0.866	0.730/0.945	3.8%	202.1	16.2%	4115.6 ± 533.1	0.907	0.806/0.962	5.1%	211.3	14.2%
$\Sigma[R1:R10]$	1431.2 ± 185.5	0.901	0.794/0.960	3.9%	62.2	12.1%	1730.7 ± 237.0	0.922	0.834/0.968	4.0%	69.0	11.1%
$\Sigma[R11:R20]$	1134.3 ± 146.9	0.852	0.704/0.938	4.4%	82.7	20.2%	1342.1 ± 188.4	0.882	0.758/0.951	7.3%	98.2	20.3%
$\Sigma[R21:R30]$	898.9 ± 110.7	0.744	0.526/0.888	5.4%	90.1	27.8%	1042.8 ± 131.9	0.794	0.605/0.912	9.1%	94.4	25.1%
$\Sigma[R1:R5]$	757.5 ± 100.0	0.912	0.815/0.964	3.7%	36.7	13.4%	916.0 ± 127.0	0.927	0.845/0.970	4.7%	43.5	13.2%
$\Sigma[R6:R10]$	673.7 ± 87.5	0.860	0.718/0.942	4.4%	33.6	13.8%	814.7 ± 112.8	0.878	0.751/0.950	5.3%	43.2	14.7%
$\Sigma[R11:R15]$	599.2 ± 76.8	0.844	0.689/0.935	4.7%	41.2	19.0%	714.2 ± 100.3	0.867	0.731/0.945	7.8%	55.7	21.6%
$\Sigma[R16:R20]$	535.1 ± 71.7	0.834	0.672/0.930	4.9%	45.2	23.4%	628.0 ± 89.7	0.874	0.744/0.948	7.9%	49.6	21.9%
$\Sigma[R21:R25]$	477.4 ± 59.1	0.786	0.591/0.908	5.0%	35.7	20.7%	554.5 ± 72.6	0.820	0.647/0.924	8.2%	45.6	22.8%
$\Sigma[R26:R30]$	421.4 ± 53.6	0.669	0.417/0.850	6.6%	57.0	37.5%	488.3 ± 61.5	0.728	0.501/0.880	11.0%	53.9	30.6%
Fatigability derived parameters: quotient of the last n repetitions by the first n repetitions												
$\frac{WR_1}{BR_1}$	0.48 ± 0.06	0.474	0.177/0.738	18.8%	0.09	49.6%	0.47 ± 0.06	0.515	0.223/0.763	14.9%	0.07	43.1%
$\frac{[R29:R30]}{[R1:R2]}$	0.52 ± 0.07	0.574	0.293/0.798	17.3%	0.09	47.1%	0.50 ± 0.07	0.525	0.234/0.769	12.0%	0.06	35.7%
$\frac{[R28:R30]}{[R1:R3]}$	0.53 ± 0.07	0.659	0.403/0.845	15.1%	0.08	41.1%	0.51 ± 0.07	0.604	0.330/0.815	11.8%	0.06	34.0%
$\log\frac{[R26:R30]}{[R1:R5]}$	−0.59 ± 0.11	0.625	0.358/0.827	25.4%	0.15	69.9%	−0.63 ± 0.12	0.618	0.348/0.823	20.6%	0.13	56.5%
$\log\frac{[R21:R30]}{[R1:R10]}$	−0.46 ± 0.09	0.645	0.383/0.837	21.7%	0.10	59.5%	−0.51 ± 0.09	0.598	0.323/0.812	19.6%	0.10	53.2%
Fatigability derived parameters: quotient of the last n repetitions by the first y repetitions												
$\frac{[R29:R30]}{[R1:R3]}$	0.53 ± 0.07	0.626	0.358/0.827	17.0%	0.09	45.0%	0.51 ± 0.07	0.546	0.259/0.782	11.8%	0.06	33.7%
$\frac{[R29:R30]}{[R1:R5]}$	0.54 ± 0.07	0.642	0.38/0.836	14.8%	0.08	41.3%	0.52 ± 0.07	0.546	0.260/0.782	11.5%	0.06	31.8%
$\frac{[R29:R30]}{[R1:R10]}$	0.57 ± 0.06	0.644	0.383/0.837	14.0%	0.08	37.6%	0.54 ± 0.06	0.518	0.227/0.765	11.1%	0.06	29.0%
$\frac{[R28:R30]}{[R1:R2]}$	0.53 ± 0.07	0.604	0.331/0.815	15.1%	0.08	43.3%	0.51 ± 0.07	0.582	0.303/0.803	13.7%	0.07	36.1%
$\log\frac{[R28:R30]}{[R1:R5]}$	−0.62 ± 0.12	0.673	0.422/0.852	22.6%	0.14	64.3%	−0.66 ± 0.12	0.617	0.347/0.822	18.2%	0.12	50.9%
$\log\frac{[R28:R30]}{[R1:R10]}$	−0.56 ± 0.11	0.687	0.442/0.860	23.2%	0.13	64.3%	−0.60 ± 0.11	0.612	0.341/0.820	18.3%	0.11	50.2%
$\frac{[R26:R30]}{[R1:R2]}$	0.54 ± 0.07	0.565	0.281/0.793	16.7%	0.09	43.8%	0.53 ± 0.07	0.589	0.311/0.807	13.2%	0.07	37.1%
$\frac{[R26:R30]}{[R1:R3]}$	0.55 ± 0.07	0.617	0.347/0.822	14.5%	0.08	41.9%	0.53 ± 0.06	0.607	0.334/0.817	13.2%	0.07	35.5%
$\log\frac{[R26:R30]}{[R1:R10]}$	−0.53 ± 0.10	0.636	0.371/0.833	26.4%	0.14	71.8%	−0.57 ± 0.11	0.614	0.343/0.821	21.1%	0.12	57.7%
$\log\frac{[R21:R30]}{[R1:R2]}$	−0.56 ± 0.11	0.534	0.246/0.775	23.2%	0.13	65.7%	−0.59 ± 0.12	0.557	0.273/0.789	22.0%	0.13	60.5%

Published in : Isokinetics and Exercise Science (2019), vol. 27, no.1, pp. 41-54
DOI: 10.3233/IES-176210
Status : Postprint (Author's version)

Table 4, continued

	Peak moment						Maximal work					
	Mean ± SD (N·m)	ICC	ICC CI 95%	CV	SEM	MDC	Mean ± SD (J)	ICC	ICC CI 95%	CV	SEM	MDC
Fatigability derived parameters: quotient of the last n repetitions by the first y repetitions												
$\log \frac{\overline{[R21:R30]}}{\overline{[R1:R3]}}$	-0.54 ± 0.10	0.590	0.313/0.807	24.1%	0.13	63.8%	-0.58 ± 0.11	0.576	0.296/0.800	20.7%	0.12	57.8%
$\log \frac{\overline{[R21:R30]}}{\overline{[R1:R5]}}$	-0.52 ± 0.10	0.624	0.356/0.826	21.2%	0.11	59.8%	-0.56 ± 0.10	0.594	0.318/0.810	19.6%	0.11	55.2%
Fatigability derived parameters: quotient of n repetitions by the y best repetitions												
$\log \left[\frac{\Sigma[R1:R30]}{BR_1}\right]$	3.07 ± 0.06	0.423	0.123/0.705	2.3%	0.07	6.1%	3.06 ± 0.06	0.495	0.200/0.751	2.6%	0.08	7.5%
$\frac{\overline{[R29:R30]}}{BR_1}$	0.51 ± 0.07	0.591	0.314/0.808	15.7%	0.08	41.2%	0.49 ± 0.07	0.529	0.239/0.772	12.2%	0.06	35.6%
$\frac{\overline{[R28:R30]}}{BR_1}$	0.51 ± 0.06	0.629	0.363/0.829	13.7%	0.07	37.4%	0.49 ± 0.06	0.592	0.316/0.809	12.2%	0.06	35.6%
$\frac{\overline{[R26:R30]}}{BR_1}$	0.53 ± 0.06	0.583	0.304/0.803	13.2%	0.07	37.8%	0.51 ± 0.06	0.590	0.313/0.808	13.7%	0.07	37.5%
$\frac{\overline{[R21:R30]}}{BR_1}$	0.56 ± 0.06	0.580	0.300/0.802	10.7%	0.06	29.5%	0.54 ± 0.06	0.591	0.314/0.808	13.0%	0.07	33.7%
$\frac{\overline{[R29:R30]}}{\overline{[BR_1:BR_2]}}$	0.51 ± 0.07	0.620	0.351/0.824	15.7%	0.08	41.0%	0.50 ± 0.06	0.540	0.253/0.779	12.0%	0.06	33.9%
$\frac{\overline{[R29:R30]}}{\overline{[BR_1:BR_3]}}$	0.52 ± 0.07	0.681	0.433/0.856	15.4%	0.08	41.9%	0.50 ± 0.06	0.603	0.330/0.815	12.0%	0.06	33.3%
$\frac{\overline{[R29:R30]}}{\overline{[BR_2:BR_3]}}$	0.53 ± 0.07	0.670	0.418/0.851	15.1%	0.08	42.6%	0.51 ± 0.06	0.542	0.255/0.780	11.8%	0.06	32.2%
$\frac{\overline{[R28:R30]}}{\overline{[BR_1:BR_3]}}$	0.53 ± 0.07	0.681	0.433/0.856	13.2%	0.07	38.0%	0.51 ± 0.06	0.603	0.330/0.815	11.8%	0.06	33.3%
$\log \frac{\overline{[R28:R30]}}{\overline{[BR_2:BR_4]}}$	-0.61 ± 0.12	0.690	0.446/0.861	24.6%	0.15	66.5%	-0.66 ± 0.12	0.612	0.341/0.820	18.2%	0.12	50.2%
$\log \frac{\overline{[R26:R30]}}{\overline{[BR_1:BR_5]}}$	-0.59 ± 0.11	0.628	0.361/0.828	25.4%	0.15	68.5%	-0.63 ± 0.12	0.613	0.341/0.820	20.6%	0.13	56.4%
$\log \frac{\overline{[R26:R30]}}{\overline{[BR_2:BR_6]}}$	-0.56 ± 0.11	0.633	0.368/0.831	26.8%	0.15	72.0%	-0.61 ± 0.11	0.610	0.338/0.819	19.7%	0.12	56.6%
$\log \frac{\overline{[R21:R30]}}{\overline{[BR_1:BR_{10}]}}$	-0.47 ± 0.09	0.647	0.386/0.838	21.3%	0.10	58.2%	-0.51 ± 0.09	0.598	0.323/0.812	19.6%	0.10	52.8%
$\log \frac{\overline{[R21:R30]}}{\overline{[BR_2:BR_{11}]}}$	-0.44 ± 0.08	0.655	0.398/0.843	20.5%	0.09	59.0%	-0.48 ± 0.09	0.594	0.318/0.810	18.8%	0.09	53.3%
Fatigability derived parameters: quotient of n repetitions by the y best consecutives repetitions												
$\frac{\overline{[R29:R30]}}{\overline{CBR_2}}$	0.52 ± 0.07	0.618	0.348/0.823	15.4%	0.08	42.4%	0.50 ± 0.07	0.542	0.254/0.780	12.0%	0.06	34.7%
$\log \frac{\overline{[R28:R30]}}{\overline{CBR_3}}$	-0.64 ± 0.12	0.670	0.419/0.851	23.4%	0.15	62.9%	-0.68 ± 0.13	0.612	0.340/0.819	19.1%	0.13	51.1%
$\log \frac{\overline{[R26:R30]}}{\overline{CBR_5}}$	-0.59 ± 0.11	0.626	0.358/0.827	23.7%	0.14	68.4%	-0.63 ± 0.12	0.612	0.340/0.820	20.6%	0.13	55.7%
$\log \frac{\overline{[R21:R30]}}{\overline{CBR_{10}}}$	-0.46 ± 0.09	0.644	0.383/0.837	21.7%	0.10	59.4%	-0.51 ± 0.09	0.597	0.322/0.811	19.6%	0.10	52.9%
$\log \frac{\overline{CWR_2}}{\overline{CBR_2}}$	-0.59 ± 0.11	0.458	0.160/0.728	27.1%	0.16	73.4%	-0.63 ± 0.11	0.516	0.224/0.764	25.4%	0.16	72.1%
$\log \frac{\overline{CWR_3}}{\overline{CBR_3}}$	-0.56 ± 0.10	0.526	0.236/0.770	25.0%	0.14	68.3%	-0.6 ± 0.11	0.521	0.230/0.767	21.7%	0.13	61.8%
$\log \frac{\overline{CWR_5}}{\overline{CBR_5}}$	-0.51 ± 0.10	0.573	0.292/0.798	21.6%	0.11	60.1%	-0.55 ± 0.10	0.543	0.256/0.780	20.0%	0.11	57.2%
$\log \frac{\overline{CWR_{10}}}{\overline{CBR_{10}}}$	-0.46 ± 0.09	0.644	0.383/0.837	21.7%	0.10	59.6%	-0.51 ± 0.09	0.597	0.321/0.811	19.6%	0.10	53.1%
Fatigability derived parameters: quotient of the last n repetitions by the first n repetitions												
$\frac{R_{29}}{R_2}$	0.53 ± 0.07	0.627	0.360/0.828	17.0%	0.09	47.7%	0.51 ± 0.07	0.545	0.258/0.782	11.8%	0.06	33.8%
$\frac{WR_2}{BR_2}$	0.53 ± 0.07	0.644	0.383/0.837	15.1%	0.08	40.0%	0.50 ± 0.06	0.572	0.291/0.797	14.0%	0.07	40.8%
$\frac{WR_2}{BR_1}$	0.51 ± 0.07	0.602	0.328/0.814	13.7%	0.07	39.0%	0.49 ± 0.06	0.551	0.265/0.785	16.3%	0.08	44.2%
$\frac{WR_1}{BR_2}$	0.50 ± 0.07	0.488	0.193/0.747	18.0%	0.09	50.7%	0.48 ± 0.06	0.510	0.218/0.761	14.6%	0.07	40.3%

Note: $BR_x = x^{\text{th}}$ Best Repetition; $WR_x = x^{\text{th}}$ Worst Repetition; $R_x = x^{\text{th}}$ repetition; $\Sigma[Rx{:}Ry]$ = cumulated performance from x^{th} to y^{th} repetition; $\overline{[Rx{:}Ry]}$ average performance from x^{th} to y^{th} repetition; $[BR_x{:}BR_y]$ = average performance from x^{th} better to y^{th} better repetition; $\overline{CBR_x}$ = average performance of best x consecutives repetitions; $\overline{CWR_x}$ = average performance of worst x consecutives repetitions.

Published in : Isokinetics and Exercise Science (2019), vol. 27, no.1, pp. 41-54
DOI: 10.3233/IES-176210
Status : Postprint (Author's version)

3.1 REPRODUCIBILITY OF FATIGABILITY PARAMETERS FOR KNEE EXTENSORS

The reproducibility of data collected on knee extensors is presented in Table 4.

The fatigability measured parameters, with the exception of partial sum #26–#30 ($\Sigma[R26{:}R30]$ – ICC_{PM} =0.669 [0.417/0.850] and ICC_{MW}= 0.728 [0.501/ 0.880]), demonstrated high to excellent relative reproducibility. Their ICC, whether for the PM or the MW, were almost all higher than 0.8 and upper, in some cases, than 0.9. The MDC of the measured parameters were ranged from 12.1% to 37.5% for the PM and from 11.1% to 30.6% for the MW. For the best repetition, the total sum and for the first partials sums (#1–#10, #1–#5 and #6–#10), the SEM score criterion for acceptable precision was met, while it was almost met for the intermediary partials sums (#11–#20 and #11–#15 both for the PM and the MW with in addition #16–#20 for the MW). Rather, it was not met for the last partials sums (#21–#30, #21–#30 and #26–#30 with in addition #16–#20 for the PM). The repeated measures ANOVA revealed no significant difference among the testing sessions, as shown by the lack of main effect of the testing session ($p > 0.05$) for all measured parameters.

The relative reproducibility of the fatigability derived parameters was (at best) moderate: the ICC, for PM and MW, was <0.7. The MDC score, for PM and MW, of all derived parameters was considerably higher than 29.0% (except for the quotient of the total sum by the best repetition – $\log(\Sigma[R1{:}R30]/\text{BR }1)$– MDC_{PM}= 6.1% and MDC_{MW}= 7.5%) and none of the SEM scores met the criterion for acceptable precision. The repeated measures ANOVA revealed no significant difference among the testing sessions, as shown by the lack of main effect of the testing session ($p > 0.05$) for a large majority of derived parameters. When a significant main effect was detected, adjusted pairwise comparisons revealed that session #1 was significantly different from session #2 (p-value about 0.03–0.04), with a non-uniform superiority of one session to the other.

The r^2 determination coefficient of linear regression of the performance was 0.96 $\pm$0.03 and 0.95 $\pm$0.03 for the PM and MW while the slope was -2.64 ± 0.62 and -3.39 ± 0.80 for the PM and MW. The PCC between PM and MW for extensors over the three testing sessions was 0.987 (with p-value <0.001). By crossing the information provided by the slope and the PCC, we detected that the induced fatigue caused a very significant decrease 1.28 times greater in MW than in PM ($p < 0.0001$), although PM and MW were very strongly correlated.

Relative and absolute variability between consecutive repetitions showed low reproducibility, with ICC less than 0.4 for knee extensors, MDC score higher than 70.0% and none of the SEM scores met the criterion for acceptable precision, for PM as well as MW (see Table 3). The relative variability was nevertheless strongly and positively correlated with the progress of the testing session (PCC_{PM}= 0.739 with p-value <0.001; PCC_{MW}= 0.781 with p-value <0.001).

3.2 REPRODUCIBILITY OF FATIGABILITY PARAMETERS FOR KNEE FLEXORS

The data reproducibility for knee flexors is presented in Table 5.

Published in : Isokinetics and Exercise Science (2019), vol. 27, no.1, pp. 41-54
DOI: 10.3233/IES-176210
Status : Postprint (Author's version)

Table 5. Knee flexors parameters peak moment and maximal work mean value ±standard deviation, ICC, ICC CI 95%, CV, SEM (expressed in N·m for PM and in J for MW) and MDC

	Peak moment						Maximal work					
	Mean ± SD (N·m)	ICC	ICC CI 95%	CV	SEM	MDC	Mean ± SD (J)	ICC	ICC CI 95%	CV	SEM	MDC
Fatigability measured parameters												
BR_1	87.6 ± 13.7	0.750	0.535/0.891	13.0%	11.4	36.0%	115.2 ± 17.3	0.674	0.423/0.853	13.3%	15.3	36.8%
$\Sigma[R1{:}R30]$	1885.5 ± 307.1	0.810	0.603/0.919	18.7%	352.5	51.8%	2320.9 ± 391.0	0.781	0.584/0.906	16.8%	390.2	46.6%
$\Sigma[R1{:}R10]$	789.5 ± 132.3	0.771	0.567/0.901	15.4%	121.3	42.6%	1014.3 ± 168.6	0.728	0.501/0.880	13.5%	136.8	37.4%
$\Sigma[R11{:}R20]$	618.1 ± 106.1	0.773	0.570/0.902	17.2%	106.4	47.7%	754.1 ± 135.8	0.743	0.524/0.888	14.9%	112.1	41.2%
$\Sigma[R21{:}R30]$	477.9 ± 86.7	0.722	0.493/0.877	28.7%	137.2	79.6%	552.5 ± 111.8	0.716	0.483/0.874	29.7%	164.2	82.4%
$\Sigma[R1{:}R5]$	414.4 ± 67.3	0.741	0.520/0.887	15.3%	63.2	42.3%	538.2 ± 84.8	0.696	0.454/0.864	13.4%	72.2	37.2%
$\Sigma[R6{:}R10]$	375.1 ± 66.7	0.777	0.578/0.904	15.9%	59.6	44.1%	476.0 ± 86.5	0.733	0.510/0.883	14.1%	67.1	39.1%
$\Sigma[R11{:}R15]$	330.2 ± 56.4	0.779	0.581/0.905	15.1%	49.8	41.8%	409.3 ± 73.3	0.752	0.537/0.892	12.0%	49.0	33.2%
$\Sigma[R16{:}R20]$	287.9 ± 51.9	0.708	0.472/0.870	20.4%	58.6	56.5%	344.8 ± 65.6	0.685	0.439/0.859	19.4%	66.9	53.8%
$\Sigma[R21{:}R25]$	257.0 ± 44.1	0.721	0.491/0.877	27.2%	69.8	75.3%	299.6 ± 56.5	0.704	0.466/0.868	26.4%	79.1	73.2%
$\Sigma[R26{:}R30]$	221.0 ± 44.4	0.680	0.432/0.856	31.1%	68.8	86.3%	252.9 ± 57.3	0.690	0.447/0.861	34.2%	86.5	94.8%
Fatigability derived parameters: quotient of the last n repetitions by the first n repetitions												
$\frac{WR_1}{BR_1}$	0.45 ± 0.1	0.438	0.139/0.715	28.9%	0.13	78.2%	0.39 ± 0.10	0.387	0.088/0.681	30.8%	0.12	85.7%
$\frac{[R29:R30]}{[R1:R2]}$	0.50 ± 0.11	0.352	0.054/0.656	24.0%	0.12	63.9%	0.43 ± 0.10	0.405	0.105/0.693	25.6%	0.11	67.4%
$\frac{[R28:R30]}{[R1:R3]}$	0.52 ± 0.11	0.372	0.073/0.670	25.0%	0.13	67.3%	0.45 ± 0.10	0.414	0.115/0.699	26.7%	0.12	72.7%
$\log\frac{[R26:R30]}{[R1:R5]}$	−0.64 ± 0.18	0.415	0.116/0.700	35.9%	0.23	98.5%	−0.77 ± 0.21	0.477	0.181/0.740	35.1%	0.27	96.3%
$\log\frac{[R21:R30]}{[R1:R10]}$	−0.50 ± 0.14	0.335	0.038/0.643	38.0%	0.19	105.6%	−0.61 ± 0.16	0.371	0.071/0.669	36.1%	0.22	98.2%
Fatigability derived parameters: quotient of the last n repetitions by the first y repetitions												
$\frac{[R29:R30]}{[R1:R3]}$	0.50 ± 0.11	0.345	0.047/0.651	22.0%	0.11	61.5%	0.44 ± 0.10	0.382	0.083/0.677	22.7%	0.10	66.6%
$\frac{[R29:R30]}{[R1:R5]}$	0.51 ± 0.11	0.335	0.038/0.644	23.5%	0.12	62.7%	0.44 ± 0.10	0.372	0.072/0.670	25.0%	0.11	69.0%
$\frac{[R29:R30]}{[R1:R10]}$	0.54 ± 0.11	0.322	0.025/0.634	22.2%	0.12	61.5%	0.47 ± 0.10	0.357	0.059/0.660	25.5%	0.12	68.9%
$\frac{[R28:R30]}{[R1:R2]}$	0.52 ± 0.11	0.382	0.083/0.677	25.0%	0.13	70.1%	0.44 ± 0.10	0.438	0.139/0.715	27.3%	0.12	73.9%
$\log\frac{[R28:R30]}{[R1:R5]}$	−0.67 ± 0.20	0.374	0.074/0.671	40.3%	0.27	110.0%	−0.81 ± 0.23	0.455	0.157/0.726	37.0%	0.30	101.4%
$\log\frac{[R28:R30]}{[R1:R10]}$	−0.62 ± 0.19	0.362	0.063/0.663	41.9%	0.26	116.6%	−0.75 ± 0.22	0.447	0.149/0.721	40.0%	0.30	109.1%
$\frac{[R26:R30]}{[R1:R2]}$	0.53 ± 0.10	0.445	0.147/0.720	20.8%	0.11	59.6%	0.46 ± 0.10	0.478	0.182/0.741	23.9%	0.11	67.7%
$\frac{[R26:R30]}{[R1:R3]}$	0.53 ± 0.10	0.429	0.130/0.709	20.8%	0.11	56.4%	0.46 ± 0.09	0.447	0.149/0.721	23.9%	0.11	65.9%
$\log\frac{[R26:R30]}{[R1:R10]}$	−0.59 ± 0.17	0.399	0.099/0.689	37.3%	0.22	105.1%	−0.71 ± 0.19	0.465	0.168/0.732	38.0%	0.27	103.7%
$\log\frac{[R21:R30]}{[R1:R2]}$	−0.57 ± 0.16	0.399	0.099/0.689	36.8%	0.21	103.9%	−0.7 ± 0.18	0.469	0.172/0.735	31.4%	0.22	88.2%
$\log\frac{[R21:R30]}{[R1:R3]}$	−0.57 ± 0.15	0.366	0.067/0.666	33.3%	0.19	95.4%	−0.69 ± 0.18	0.410	0.111/0.697	30.4%	0.21	84.8%
$\log\frac{[R21:R30]}{[R1:R5]}$	−0.55 ± 0.15	0.352	0.054/0.656	36.4%	0.20	98.4%	−0.68 ± 0.17	0.406	0.106/0.693	32.4%	0.22	89.7%
Fatigability derived parameters: quotient of n repetitions by the y best repetitions												
$\log\left[\frac{\Sigma[R1:R30]}{BR_1}\right]$	3.07 ± 0.07	0.427	0.128/0.708	2.9%	0.09	8.4%	3.00 ± 0.09	0.479	0.183/0.742	3.0%	0.09	8.1%
$\frac{[R29:R30]}{BR_1}$	0.48 ± 0.10	0.350	0.051/0.654	25.0%	0.12	67.5%	0.41 ± 0.10	0.399	0.100/0.689	24.4%	0.10	69.6%
$\frac{[R28:R30]}{BR_1}$	0.49 ± 0.10	0.374	0.075/0.671	26.5%	0.13	74.6%	0.43 ± 0.10	0.430	0.131/0.710	27.9%	0.12	76.7%
$\frac{[R26:R30]}{BR_1}$	0.51 ± 0.09	0.431	0.132/0.710	23.5%	0.12	64.6%	0.44 ± 0.09	0.464	0.167/0.732	25.0%	0.11	71.2%
$\frac{[R21:R30]}{BR_1}$	0.55 ± 0.08	0.416	0.117/0.701	20.0%	0.11	57.2%	0.48 ± 0.08	0.436	0.137/0.714	20.8%	0.10	59.0%
$\frac{[R29:R30]}{[BR_1:BR_2]}$	0.49 ± 0.10	0.348	0.050/0.653	24.5%	0.12	68.3%	0.42 ± 0.10	0.389	0.089/0.682	26.2%	0.11	72.5%

Published in : Isokinetics and Exercise Science (2019), vol. 27, no.1, pp. 41-54
DOI: 10.3233/IES-176210
Status : Postprint (Author's version)

Table 5, continued

	Peak moment						Maximal work					
	Mean ± SD (N·m)	ICC	ICC CI 95%	CV	SEM	MDC	Mean ± SD (J)	ICC	ICC CI 95%	CV	SEM	MDC
Fatigability derived parameters: quotient of n repetitions by the y best repetitions												
$\frac{\overline{[R29:R30]}}{\overline{[BR_1:BR_3]}}$	0.49 ± 0.10	0.373	0.074/0.671	24.5%	0.12	67.4%	0.43 ± 0.10	0.412	0.112/0.698	25.6%	0.11	73.9%
$\frac{\overline{[R29:R30]}}{\overline{[BR_2:BR_3]}}$	0.5 ± 0.11	0.350	0.051/0.654	24.0%	0.12	67.7%	0.44 ± 0.10	0.372	0.073/0.670	27.3%	0.12	77.0%
$\frac{\overline{[R28:R30]}}{\overline{[BR_1:BR_3]}}$	0.50 ± 0.10	0.373	0.074/0.671	28.0%	0.14	74.6%	0.44 ± 0.10	0.412	0.112/0.698	29.5%	0.13	81.5%
$\log\frac{\overline{[R28:R30]}}{\overline{[BR_2:BR_4]}}$	−0.68 ± 0.20	0.372	0.072/0.67	42.6%	0.29	116.3%	−0.82 ± 0.23	0.442	0.143/0.717	39.0%	0.32	110.1%
$\log\frac{\overline{[R26:R30]}}{\overline{[BR_1:BR_5]}}$	−0.65 ± 0.17	0.416	0.116/0.700	36.9%	0.24	104.1%	−0.78 ± 0.20	0.476	0.180/0.739	35.9%	0.28	101.3%
$\log\frac{\overline{[R26:R30]}}{\overline{[BR_2:BR_6]}}$	−0.62 ± 0.17	0.414	0.114/0.699	38.7%	0.24	105.9%	−0.75 ± 0.20	0.476	0.179/0.739	38.7%	0.29	105.4%
$\log\frac{\overline{[R21:R30]}}{\overline{[BR_1:BR_{10}]}}$	−0.51 ± 0.14	0.352	0.053/0.656	37.3%	0.19	106.0%	−0.62 ± 0.16	0.393	0.093/0.685	35.5%	0.22	100.9%
$\log\frac{\overline{[R21:R30]}}{\overline{[BR_2:BR_{11}]}}$	−0.49 ± 0.13	0.345	0.047/0.651	38.8%	0.19	109.2%	−0.59 ± 0.15	0.382	0.082/0.677	39.0%	0.23	106.5%
Fatigability derived parameters: quotient of n repetitions by the y best consecutives repetitions												
$\frac{\overline{[R29:R30]}}{\overline{CBR_2}}$	0.49 ± 0.10	0.348	0.050/0.653	24.5%	0.12	69.6%	0.42 ± 0.10	0.384	0.084/0.678	26.2%	0.11	73.4%
$\log\frac{\overline{[R28:R30]}}{\overline{CBR_3}}$	−0.70 ± 0.20	0.371	0.072/0.670	40.0%	0.28	110.0%	−0.84 ± 0.23	0.448	0.150/0.722	35.7%	0.30	99.9%
$\log\frac{\overline{[R26:R30]}}{\overline{CBR_5}}$	−0.64 ± 0.17	0.407	0.108/0.695	37.5%	0.24	102.3%	−0.77 ± 0.20	0.468	0.171/0.734	36.4%	0.28	99.8%
$\log\frac{\overline{[R21:R30]}}{\overline{CBR_{10}}}$	−0.50 ± 0.14	0.332	0.035/0.641	38.0%	0.19	106.2%	−0.61 ± 0.16	0.369	0.070/0.668	36.1%	0.22	98.8%
$\log\frac{\overline{CWR_2}}{\overline{CBR_2}}$	−0.76 ± 0.21	0.401	0.101/0.690	39.5%	0.30	108.8%	−0.78 ± 0.18	0.402	0.103/0.691	34.6%	0.27	96.4%
$\log\frac{\overline{CWR_3}}{\overline{CBR_3}}$	−0.71 ± 0.19	0.412	0.113/0.698	40.8%	0.29	114.1%	−0.73 ± 0.18	0.349	0.051/0.654	34.2%	0.25	95.5%
$\log\frac{\overline{CWR_5}}{\overline{CBR_5}}$	−0.64 ± 0.17	0.413	0.114/0.698	37.5%	0.24	102.4%	−0.66 ± 0.16	0.371	0.072/0.669	33.3%	0.22	90.8%
$\log\frac{\overline{CWR_{10}}}{\overline{CBR_{10}}}$	−0.50 ± 0.14	0.330	0.033/0.640	38.0%	0.19	106.8%	−0.61 ± 0.16	0.368	0.069/0.667	36.1%	0.22	99.2%
Fatigability derived parameters: quotient of the last n repetitions by the first n repetitions												
$\frac{R_{29}}{R_2}$	0.51 ± 0.12	0.380	0.080/0.675	25.5%	0.13	73.1%	0.44 ± 0.11	0.434	0.135/0.713	27.3%	0.12	76.2%
$\frac{WR_2}{BR_2}$	0.49 ± 0.09	0.438	0.139/0.715	26.5%	0.13	73.5%	0.43 ± 0.09	0.470	0.174/0.736	30.2%	0.13	82.6%
$\frac{WR_2}{BR_1}$	0.48 ± 0.09	0.460	0.163/0.729	25.0%	0.12	71.0%	0.41 ± 0.09	0.493	0.198/0.750	26.8%	0.11	75.2%
$\frac{WR_1}{BR_2}$	0.46 ± 0.10	0.422	0.122/0.704	28.3%	0.13	80.1%	0.40 ± 0.10	0.358	0.059/0.660	32.5%	0.13	92.4%

Note: $BR_x = x^{th}$ Best Repetition; $WR_x = x^{th}$ Worst Repetition; $R_x = x^{th}$ repetition; $\Sigma[Rx{:}Ry]$ = cumulated performance from x^{th} to y^{th} repetition; $\overline{[Rx{:}Ry]}$ = average performance from x^{th} to y^{th} repetition; $[BR_x{:}BR_y]$ = average performance from x^{th} better to y^{th} better repetition; $\overline{CBR_x}$ = average performance of best x consecutives repetitions; $\overline{CWR_x}$ =average performance of worst x consecutives repetitions.

Only the total sum ($\Sigma[R1{:}R30]$) had high relative reproducibility (ICC_{PM}= 0.810 [0.630/0.919], ICC_{MW}= 0.781 [0.584/0.906]). For PM, the ICC of the measured parameters were between 0.7 and 0.8, except for the partial sum #26–#30 ($\Sigma[R26{:}R30]$ – ICC_{PM}= 0.680 [0.432/0.856]); their relative reproducibility was high. For MW, with ICC ranging between 0.67 and 0.8, the relative reproducibility of the measured parameters was moderate to high. The MDC of all measured parameters were considerably higher than 30.0%, for the PM and the MW, and the SEM score did not meet the criterion for acceptable precision. The repeated measures ANOVA p-values for the main effect were higher than 0.05 for the best repetition and for the first partials sums (#1–#10, #11–#20, #1–#5, #6–#10 and #11–#15) but for the total sum and the last partials sums (#21–#30, #16–#20, #21–#25, and #26–#30), the p-value were lower than 0.05. When a significant main effect was detected, the session #2 vs session #3 adjusted pairwise comparisons resulted in no significant difference.

Published in : Isokinetics and Exercise Science (2019), vol. 27, no.1, pp. 41-54
DOI: 10.3233/IES-176210
Status : Postprint (Author's version)

All fatigability derived parameters had an ICC lower than 0.52, whether for PM or MW, and, therefore, had a weak (to moderate) relative reproducibility. The MDC of all derived parameters were higher than 55.0% (for the PM and the MW) except for the quotient of the total sum by the best repetition ($\log(\Sigma[R1{:}R30]/\text{BR}\,1)$ – SEM_{PM}= 8.4% and SEM_{MW}= 8.1%) and no SEM score met the criterion for acceptable precision. The r^2 determination coefficient of linear regression of the performance was 0.89 $\pm$0.10 and 0.92 $\pm$0.06 for the PM and MW. The repeated measures ANOVA revealed no significant main effects for any of the derived parameters.

The reproducibility of the fatigability measured and derived parameters for the flexors was lower than for the extensors either for the PM or the MW (the ICC was steadily equal or higher while the CV_{ME}%, SEM and MDC were steadily equal or lower for the extensors than for the flexors, except for the PM of $\frac{\Sigma[R1:R30]}{\text{BR}_1}$and of $\Sigma[R26{:}R30]$).

The r^2 determination coefficient of linear regression of the performance was 0.89 $\pm$0.10 and 0.92 $\pm$0.06 for the PM and MW while the slope was -1.52 $\pm$0.47 and -2.24 $\pm$0.63 for the PM and MW. The PCC between PM and MW for flexors over the three testing sessions was 0.977 (with p-value <0.001). By crossing the information provided by the slope and the PCC, we detected that the induced fatigue caused a very significant decrease 1.48 times greater in MW than in PM ($p < 0.0001$), although PM and MW were very strongly correlated.

The PCC between the extensors and the flexors was 0.807 and 0.796 respectively for the PM and MW (with p-value <0.001). By crossing the information provided by the slope of linear regression previously mentioned and these PCC, we noticed that the induced fatigue caused a decrease 1.74 and 1.51 times greater in extensors than in flexors, respectively for PM and MW, although the extensors and the flexors were (very) strongly correlated.

Relative and absolute variability between consecutive repetitions showed low reproducibility with ICC less than 0.5 for knee flexors, MDC score higher than 60.0% and none of the SEM scores met the criterion for acceptable precision, for PM and MW (see Table 3). The relative variability was nevertheless strongly and positively correlated with the progress of the testing session (PCC_{PM}= 0.797 with p-value <0.001; PCC_{MW}= 0.700 with p-value <0.001).

4. Discussion

Although Lambert et al. [61], Pincivero et al. [13, 14] and Saenz et al. [33] demonstrated that the measured parameters of fatigability assessment are reliable by contrast with the derived parameters, we have to specify that the different authors have analyzed only one derived parameter by research (respectively, ratio between the 15 first and the 15 last repetitions, between the 5 first and the 5 last repetitions, between the 10 first and the 10 last repetitions and between the 13 first and the 13 last repetitions). Respectively in 2000 and 2011, Pincivero et al. [13] and Ferriero et al. [62] have briefly questioned the utilization of the fatigability derived parameters for the assessment of the decrease in performance but, to our knowledge, no previous research has comprehensively

Published in : Isokinetics and Exercise Science (2019), vol. 27, no.1, pp. 41-54
DOI: 10.3233/IES-176210
Status : Postprint (Author's version)

studied the intra-dynamometer reproducibility of those fatigability derived parameters employed for the isokinetic evaluation of knee fatigability in concentric conditions. In the present investigation we conducted a reproducibility study that included the most exhaustive number of logical combinations of measured and derived parameters regularly provided by the isokinetic devices or used by clinicians or researchers, as listed in the *data analysis* section.

For the measured parameters, our data corroborate previous research: almost all showed excellent relative reproducibility for knee extensors and flexors, whether for PM or MW. However: (1) the measured parameters (best repetitions, total and partial sums) have a sufficient absolute and relative reproducibility (whether for PM or MW) for evaluation also only for the extensors even if a careful consideration must be given to the partial sums at the end of testing session (#21–#30, #21–#25 and #26–#30). The lower reproducibility of the partial sums at the end of testing session can be partly explained by the patient motivation and/or the arduousness of the fatigability evaluation. This will be discussed in more detail below along with the relative and absolute variability; (2) despite the fact that their relative reproducibility is high, due to their absolute reproducibility which did not meet the criterion for acceptable precision, no fatigability measured parameters can be recommended for knee flexors.

As explained by Kean et al. [63], the MDC is "particularly useful when determining whether an observed change in score between test sessions is truly a change in subject status or is merely error (noise) in the measurement" [50]. Our SEM and MDC results for the measured parameters were, despite the appearance to the contrary, lower than a previous research that assessed the reliability of the same isokinetic device employed in the present study (Biodex System 3): observed SEM scores of about 11.8 N·m (with MDC about 21.5%) for extensors and about 8.2 N·m (with MDC about 28.6%) for flexors [64]. They used another formula for the SEM calculation ($SEM = \sqrt{MS_E}$ for Lund et al. [64] while we used $SEM = \sqrt{MS_E + MS_T}$) which leads to an under-estimation in comparison with our SEM and MDC scores. Indeed using Lund et al's formula [64], our SEM for the PM of the best repetition would have been 5.8 N·m and 6.8 N·m while our MDC scores would have been 10.0% and 7.8%, respectively for the extensors and the flexors, which in fact fall below the scores of these previous research. Based on our data, we can predict with a 95% level of confidence that the total sum of knee extensors MW of recreationally men would change by at least 210 J on repeated evaluation. Therefore, for instance, if the total sum of knee extensors MW in a recreationally man was 5012 J, and after training this total sum is found increased to 5383 J, we could be confident that the subject performance had truly improved because the delta of performance of 371 J exceeds the MDC of 210 J.

The lower relative and absolute reproducibility of the knee flexors, demonstrated by the higher scores of ICC or ANOVA main effect p-value and the lower scores of CV_{ME}%, SEM or relative MDC results for extensors, can be explained by the lack of specificity of the task as explained by Bosquet et al. [6] and Croisier [65]. Indeed, the hamstring muscles produce seldom repetitive maximal concentric contractions in real life or in sport situations; in sports, the functional role of the hamstrings is to decelerate, eccentrically, the lower leg during rapid concentric contractions of the

Published in : Isokinetics and Exercise Science (2019), vol. 27, no.1, pp. 41-54
DOI: 10.3233/IES-176210
Status : Postprint (Author's version)

knee extensors [6]. Nonetheless, a familiarization session seems to enhance the reproducibility of the knee flexors. This finding corroborates the hypothesis of a lack of specificity of the hamstrings.

As mentioned by Bosquet et al. [6], PM and MW are not affected identically by muscle fatigue induction. Indeed, the PM and the MW are very strongly correlated to one another (PCC around 0.98), whether it is for the extensors or the flexors, but the induced fatigue causes a decrease of 1.28 and 1.48 times greater in MW than in PM, for the extensors and the flexors, respectively. These observations confirm that it is imperative to assess isokinetic fatigue using the developed MW and not just the PM, according to the different, and therefore non-redundant, information that the MW provides in the context of fatigability resistance evaluation.

Even though the performance of the extensors and the flexors are strongly correlated (PCC around 0.80), the extensors are likely to tire out faster and to a greater extent than the flexors. Two lines of explanation of this phenomenon may be suggested: (1) the greatest absolute force of the extensors compared to the flexors can lead to greater fatigability. Indeed, at equal relative strength, a greater absolute moment seems to accelerate the induction of neuromuscular fatigue [66, 67, 68]. Considering the extensors best performance is 1.78 and 1.62 times greater than the flexors, this factor can, at least partially, explain the observed difference between the extensors and the flexors; (2) as previously explained, the knee flexors produce seldom repetitive maximal concentric contractions which can induce a lower relative strength production due to a lack of specificity of the task. Obviously, a lower relative strength production leads to a lower decrease in performance due to less induced fatigue [69].

The main finding emerging from our study is that whether we consider relative or absolute reproducibility the knee fatigability derived parameters should not be used due to weak reproducibility. Consequently, the diagnostic, conclusions or discussion of a study drawn from the use of the fatigability derived parameters to assessing knee isokinetic fatigability performance appears to be clearly questionable. Indeed, no fatigability derived parameter whatever the quotient of the last $n$repetitions by the first $x$repetition the quotient of the total sum by the best repetition the quotient of the worst repetition by the best, etc. (see Tables 4 and 5) proved sufficiently reproducible to be confidently employed. Whether for the knee extensors or flexors, whether for the PM or the MW, no SEM scores of fatigability derived parameters, reflecting absolute reproducibility, met the criterion for acceptable precision while the relative reproducibility for the derived parameters was, at best, moderate. The lack of relative reproducibility can be explained by the fact that the fatigability derived parameters compares the $n$first/best with the $x$last/worst repetitions: by considering the negative slope of the linear regression of the performance and the good score of the r^2 determination coefficient (between 0.89 $\pm$0.10 and 0.95 $\pm$0.03), we can assimilate the last repetitions to the worst and vice versa. As indicated by the gradual decrease of reproducibility of the partial sums (see Tables 4 and 5), the last/worst repetition showed a lower reproducibility than the others. Moreover, the relative variability is strongly and positively correlated with the progress of the testing session, which indicates that the last/worst repetitions are highly volatile. The poor reproducibility of the (relative and absolute) variability (see Table 3) means that this is not an intrinsic characteristic of the subjects or the evaluation but a factor inherent to the fatigue induced by the testing session. The subject's motivation and/or the arduousness of the fatigability testing session can potentially account for the increasing variability during the evaluation: each extension and each subsequent flexion, from the first to the thirtieth, must be achieved with maximal intensity over the entire ROM. Therefore, the subjects may have difficulty to maintain this maximal effort as the testing session proceeds if they feel discomfort caused by muscle contractions despite their full motivation and the researcher's verbal encouragement. Taking into account these elements, it makes sense that the fatigability derived parameters, because they compare the $n$first/best with the $x$last/worst repetitions, have an insufficient reproducibility.

The sample size was a limitation of this study: despite the fact that it is in agreement with the recommendation that reliability protocol should be realized on 15–20 subjects [48, 70], further studies are warranted to confirm the present results over a larger sample size. Another limitation was that this study focused only on the knee joint. As the fatigability resistance evaluations are not only relating to the knee, it would obviously be highly interesting to assess the reliability of the measured and derived parameters in of other joints. Finally, the findings of the present study, as a precautionary measure, should not be generalized to other populations than healthy male subjects.

5. Conclusions

Our results indicate that all listed fatigability *measured* parameters (see Table 1 for the complete list) can be used for knee extensors, even if careful consideration must be given to the partial sums at the end of the testing session (#21–#30, #21–#25 & #26–#30). Notably, no fatigability measured parameters can be used for knee flexors, even if the relative reproducibility of the measured parameters for flexor is high. However, the main finding is that no *derived* parameter based on PM or MW may be used for studying knee extensors or flexors fatigability.

Acknowledgments

The authors wish to thank the Wallonia-Brussels Federation for their assistance in this study.

Conflict of interest

The authors declare that there are no conflicts of interest in undertaking this study.

Published in : Isokinetics and Exercise Science (2019), vol. 27, no.1, pp. 41-54
DOI: 10.3233/IES-176210
Status : Postprint (Author's version)

References

1. Taylor, J.D., and Fletcher, J.P. Correlation between the 8-repetition maximum test and isokinetic dynamometry in the measurement of muscle strength of the knee extensors: A concurrent validity study. *Physiotherapy Theory and Practice*, 2013. 29(4): 335-341.

2. Feiring, D.C. Ellenbecker, T.S., and Derscheid, G.L. Test-retest reliability of the biodex isokinetic dynamometer. *J Orthop Sports Phys Ther*, 1990. 11(7): 298-300.

3. Gleeson, N.P., and Mercer, T.H. The utility of isokinetic dynamometry in the assessment of human muscle function. *Sports Med*, 1996. 21(1): 18-34.

4. Eken, M.M. Dallmeijer, A.J. Houdijk, H., and Doorenbosch, C.A. Muscle fatigue during repetitive voluntary contractions: a comparison between children with cerebral palsy, typically developing children and young healthy adults. *Gait & Posture*, 2013. 38(4): 962-7.

5. Maquet, D. Croisier, J.L. Renard, C., and Crielaard, J.M. Muscle performance in patients with fibromyalgia. *Joint Bone Spine*, 2002. 69(3): 293-299.

6. Bosquet, L. Maquet, D. Forthomme, B. Nowak, N. Lehance, C., and Croisier, J.L. Effect of the lengthening of the protocol on the reliability of muscle fatigue indicators. *International Journal of Sports Medicine*, 2010. 31(2): 82-8.

7. Bigland-Ritchie, B., and Woods, J.J. Changes in muscle contractile properties and neural control during human muscular fatigue. *Muscle Nerve*, 1984. 7(9): 691-9.

8. Camara, L.C. Ritti-Dias, R.M. Meneses, A.L. D'Andrea Greve, J.M. Filho, W.J. Santarem, J.M. Forjaz, C.L. Puech-Leao, P., and Wolosker, N. Isokinetic strength and endurance in proximal and distal muscles in patients with peripheral artery disease. *Annals of Vascular Surgery*, 2012. 26(8): 1114-9.

9. Gleeson, N.P., and Mercer, T.H. Reproducibility of isokinetic leg strength and endurance characteristics of adult men and women. *European Journal of Applied Physiology & Occupational Physiology*, 1992. 65(3): 221-8.

10. Hayes, P.R. French, D.N., and Thomas, K. The effect of muscular endurance on running economy. *Journal of Strength & Conditioning Research*, 2011. 25(9): 2464-9.

11. Luna, N.M. Alonso, A.C. Brech, G.C. Mochizuki, L. Nakano, E.Y., and Greve, J.M. Isokinetic analysis of ankle and ground reaction forces in runners and triathletes. *Clinics (Sao Paulo, Brazil)*, 2012. 67(9): 1023-8.

12. Maffiuletti, N.A. Bizzini, M. Desbrosses, K. Babault, N., and Munzinger, U. Reliability of knee extension and flexion measurements using the Con-Trex isokinetic dynamometer. *Clin Physiol Funct Imaging*, 2007. 27(6): 346-53.

13. Pincivero, D.M. Gear, W.S., and Sterner, R.L. Assessment of the reliability of high-intensity quadriceps femoris muscle fatigue. *Medicine & Science in Sports & Exercise*, 2001. 33(2): 334-8.

14. Pincivero, D.M. Lephart, S.M., and Karunakara, R.A. Reliability and precision of isokinetic strength and muscular endurance for the quadriceps and hamstrings. *International Journal of Sports Medicine*, 1997. 18(2): 113-7.

15. Sangnier, S., and Tourny-Chollet, C. Comparison of the decrease in strength between hamstrings and quadriceps during isokinetic fatigue testing in semiprofessional soccer players. *International Journal of Sports Medicine*, 2007. 28(11): 952-7.

16. Segerstrom, A.B. Holmback, A.M. Hansson, O. Elgzyri, T. Eriksson, K.F. Ringsberg, K. Groop, L. Wollmer, P., and Thorsson, O. Relation between cycling exercise capacity, fiber-type composition, and lower extremity muscle strength and muscle endurance. *Journal of Strength & Conditioning Research*, 2011. 25(1): 16-22.

17. Silva, J.P. Pereira, D.S. Coelho, F.M. Lustosa, L.P. Dias, J.M., and Pereira, L.S. Clinical, functional and inflammatory factors associated with muscle fatigue and self-perceived fatigue in elderly community-dwelling women. *Revista Brasileira de Fisioterapia*, 2011. 15(3): 241-8.

18. Leikis, M.J. McKenna, M.J. Petersen, A.C. Kent, A.B. Murphy, K.T. Leppik, J.A. Gong, X., and McMahon, L.P. Exercise performance falls over time in patients with chronic kidney disease despite maintenance of hemoglobin concentration. *Clinical Journal of The American Society of Nephrology: CJASN*, 2006. 1(3): 488-95.

19. Campbell, B. Roberts, M. Kerksick, C. Wilborn, C. Marcello, B. Taylor, L. Nassar, E. Leutholtz, B. Bowden, R. Rasmussen, C. Greenwood, M., and Kreider, R. Pharmacokinetics, safety, and effects on exercise performance of L-arginine alpha-ketoglutarate in trained adult men. *Nutrition*, 2006. 22(9): 872-81.

20. Katsiaras, A. Newman, A.B. Kriska, A. Brach, J. Krishnaswami, S. Feingold, E. Kritchevsky, S.B. Li, R. Harris, T.B. Schwartz, A., and Goodpaster, B.H. Skeletal muscle fatigue, strength, and quality in the elderly: the Health ABC Study. *Journal of Applied Physiology*, 2005. 99(1): 210-6.

21. B.H.Gerdle, B., and Elert, J. The temporal occurrence of the mean power frequency shift of the electromyogram during maximum prolonged dynamic and static working cycles. *International Journal of Sports Medicine*, 1994. 15(SUPPL. 1): S32-S37.

22. Vairo, G.L. Knee flexor strength and endurance profiles after ipsilateral hamstring tendons anterior cruciate ligament reconstruction. *Archives of Physical Medicine & Rehabilitation*, 2014. 95(3): 552-61.

23. Nytroen, K. Rustad, L.A. Gude, E. Hallen, J. Fiane, A.E. Rolid, K. Holm, I. Aakhus, S., and Gullestad, L. Muscular exercise capacity and body fat predict VO(2peak) in heart transplant recipients. *Eur J Prev Cardiol*, 2014. 21(1): 21-9.

24. Paolillo, F.R. Corazza, A.V. Paolillo, A.R. Borghi-Silva, A. Arena, R. Kurachi, C., and Bagnato, V.S. Phototherapy during treadmill training improves quadriceps performance in postmenopausal women. *Climacteric*, 2014. 17(3): 285-93.

25. Paraschos, I. Hassani, A. Bassa, E. Hatzikotoulas, K. Patikas, D., and Kotzamanidis, C. Fatigue differences between adults and prepubertal males. *International Journal of Sports Medicine*, 2007. 28(11): 958-63/.

26. Rombaut, L. Malfait, F. De Wandele, I. Taes, Y. Thijs, Y. De Paepe, A., and Calders, P. Muscle mass, muscle strength, functional performance, and physical impairment in women with the hypermobility type of Ehlers-Danlos syndrome. *Arthritis Care & Research*, 2012. 64(10): 1584-92.

27. Stevens-Lapsley, J. Kluger, B.M., and Schenkman, M. Quadriceps muscle weakness, activation deficits, and fatigue with Parkinson disease. *Neurorehabilitation & Neural Repair*, 2012. 26(5): 533-41.

28. Moreau, N. Li, L., and Damiano, D.L. A feasible and reliable muscle fatigue assessment protocol for individuals with cerebral palsy. *Pediatric Physical Therapy*, 2008. 20(1): 59-65.

29. De Ste Croix, M.B. Deighan, M.A. Ratel, S., and Armstrong, N. Age- and sex-associated differences in isokinetic knee muscle endurance between young children and adults. *Applied Physiology, Nutrition, & Metabolism = Physiologie Appliquee, Nutrition et Metabolisme*, 2009. 34(4): 725-31.

30. Borghi-Silva, A. Di Thommazo, L. Pantoni, C.B. Mendes, R.G. Salvini Tde, F., and Costa, D. Non-invasive ventilation improves peripheral oxygen saturation and reduces fatigability of quadriceps in patients with COPD. *Respirology*, 2009. 14(4): 537-44.

31. Janaudis-Ferreira, T. Wadell, K. Sundelin, G., and Lindström, B. Thigh muscle strength and endurance in patients with COPD compared with healthy controls. *Respiratory Medicine*, 2006. 100(8): 1451-1457.

32. Manou, V. Arseniou, P. Gerodimos, V., and Kellis, S. Test-retest reliability of an isokinetic muscle endurance test. *Isokinetics and Exercise Science*, 2002. 10(4): 177-181.

33. Saenz, A. Avellanet, M. Hijos, E. Chaler, J. Garreta, R. Pujol, E. Sandoval, B. Buen, C., and Farreny, A. Knee isokinetic test-retest: a multicentre knee isokinetic test-retest study of a fatigue protocol. *European Journal of Physical & Rehabilitation Medicine*, 2010. 46(1): 81-8.

34. Larsson, B. Karlsson, S. Eriksson, M., and Gerdle, B. Test-retest reliability of EMG and peak torque during repetitive maximum concentric knee extensions. *Journal of Electromyography and Kinesiology*, 2003. 13(3): 281-287.

35. Selig, S.E. Carey, M.F. Menzies, D.G. Patterson, J. Geerling, R.H. Williams, A.D. Bamroongsuk, V. Toia, D. Krum, H., and Hare, D.L. Reliability of isokinetic strength and aerobic power testing for patients with chronic heart failure. *Journal of Cardiopulmonary Rehabilitation*, 2002. 22(4): 282-9.

36. Carpenter, M.R. Carpenter, R.L. Peel, J. Zukley, L.M. Angelopoulou, K.M. Fischer, I. Angelopoulos, T.J., and Rippe, J.M. The reliability of isokinetic and isometric leg strength measures among individuals with symptoms of mild osteoarthritis. *J Sports Med Phys Fitness*, 2006. 46(4): 585-9.

37. Molczyk, L. Thigpen, L.K. Eickhoff, J. Goldgar, D., and Gallagher, J.C. Reliability of testing the knee extensors and flexors in healthy adult women using a Cybex II isokinetic dynamometer. *Journal of Orthopaedic and Sports Physical Therapy*, 1991. 14(1): 37-41.

38. Jones, T.W. Howatson, G. Russell, M., and French, D.N. Validity and reproducibility of a lower limb isokinetic muscular endurance testing protocol. *Isokinetics and Exercise Science*, 2013. 21(4): 311-316.

39. Montgomery, L.C. Douglass, L.W., and Deuster, P.A. Reliability of an isokinetic test of muscle strength and endurance. *J Orthop Sports Phys Ther*, 1989. 10(8): 315-22.

40. Harriss, D.J., and Atkinson, G. Ethical standards in sport and exercise science research: 2014 update. *Int J Sports Med*, 2013. 34(12): 1025-8.

41. Drouin, J.M. Valovich-mcLeod, T.C. Shultz, S.J. Gansneder, B.M., and Perrin, D.H. Reliability and validity of the Biodex system 3 pro isokinetic dynamometer velocity, torque and position measurements. *Eur J Appl Physiol*, 2004. 91(1): 22-9.

42. Croisier, J.L. Ganteaume, S. Binet, J. Genty, M., and Ferret, J.M. Strength imbalances and prevention of hamstring injury in professional soccer players: a prospective study. *Am J Sports Med*, 2008. 36(8): 1469-75.

43. McNair, P.J. Depledge, J. Brettkelly, M., and Stanley, S.N. Verbal encouragement: effects on maximum effort voluntary muscle: action. *British Journal of Sports Medicine*, 1996. 30(3): 243-245.

44. Perrin, D.H. Robertson, R.J., and Ray, R.L. Bilateral lsokinetic Peak Torque, Torque Acceleration Energy, Power, and Work Relationships in Athletes and Nonathletes. *J Orthop Sports Phys Ther*, 1987. 9(5): 184-9.

45. Manca, A. Solinas, G. Dragone, D., and Deriu, F. Isokinetic testing of muscle performance: New concepts for strength assessment. *Isokinetics and Exercise Science*, 2015. 23(2): 69-75.

46. Morrissey, M.C. The relationship between peak torque and work of the quadriceps and hamstrings after meniscectomy. *J Orthop Sports Phys Ther*, 1987. 8(8): 405-8.

47. Dvir, Z., and David, G. Average or peak moment: which of the two is more suitable to represent isokinetic muscle strength? *Isokinetics and Exercise Science*, 1995. 5(2): 93-97.

48. Manca, A. Dvir, Z., and Deriu, F. Strength and work parameters in people with multiple sclerosis and in healthy individuals: A responsiveness study of the ankle dorsiflexors. *Isokinetics and Exercise Science*, 2017. Preprint(Preprint): 1-9.

49. Atkinson, G., and Nevill, A.M. Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. *Sports Med*, 1998. 26(4): 217-38.

50. Weir, J.P. Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. *J Strength Cond Res*, 2005. 19(1): 231-40.

51. Adsuar, J.C. Olivares, P.R. Parraca, J.A. Hernandez-Mocholi, M.A., and Gusi, N. Applicability and test-retest reliability of isokinetic shoulder abduction and adduction in women fibromyalgia patients. *Arch Phys Med Rehabil*, 2013. 94(3): 444-50.

52. Currier, D.P. Elements of research in physical therapy. 3rd ed. 1990, Baltimore: Williams, & Wilkins.

53. de Vet, H.C. Terwee, C.B. Knol, D.L., and Bouter, L.M. When to use agreement versus reliability measures. *J Clin Epidemiol*, 2006. 59(10): 1033-9.

54. Wyrwich, K.W. Nienaber, N.A. Tierney, W.M., and Wolinsky, F.D. Linking clinical relevance and statistical significance in evaluating intra-individual changes in health-related quality of life. *Med Care*, 1999. 37(5): 469-78.

55. van Kernebeek, W.G. de Schipper, A.W. Savelsbergh, G.J.P., and Toussaint, H.M. Inter-rater and test-retest (between-sessions) reliability of the 4-Skills Scan for dutch elementary school children. *Measurement in Physical Education and Exercise Science*, 2018. 22(2): 129-137.

56. Wuang, Y.P. Chang, J.J. Wang, M.H., and Lin, H.C. Test-retest reliabilities of hand-held dynamometer for lower-limb muscle strength in intellectual disabilities. *Research in Developmental Disabilities*, 2013. 34(8): 2281-2290.

57. Wuang, Y.P. Su, J.H., and Su, C.Y. Reliability and responsiveness of the Movement Assessment Battery for Children-Second Edition Test in children with developmental coordination disorder. *Developmental Medicine and Child Neurology*, 2012. 54(2): 160-165.

58. Reimer, A.M. Cox, R.F.A. Boonstra, F.N., and Nijhuis-van der Sanden, M.W.G. Measurement of Fine-Motor Skills in Young Children with Visual Impairment. *Journal of Developmental and Physical Disabilities*, 2015. 27(5): 569-590.

59. Chou, C.Y. Ou, Y.C., and Chiang, T.R. Psychometric comparisons of four disease-specific health-related quality of life measures for stroke survivors. *Clinical Rehabilitation*, 2015. 29(8): 816-829.

60. Evans, J.D. Straightforward statistics for the behavioral sciences. 1996, Pacific Grove: Brooks/Cole Pub. Co. xxii, 600 p.

61. Lambert, C.P. Archer, R.L., and Evans, W.J. Muscle strength and fatigue during isokinetic exercise in individuals with multiple sclerosis. *Medicine & Science in Sports & Exercise*, 2001. 33(10): 1613-9.

62. Ferriero, G. Colombo, R. Sartorio, F., and Vercelli, S. Reliability of the isokinetic fatigue index. *European Journal of Physical & Rehabilitation Medicine*, 2011. 47(2): 351-2.

63. Kean, C.O. Birmingham, T.B. Garland, S.J. Bryant, D.M., and Giffin, J.R. Minimal detectable change in quadriceps strength and voluntary muscle activation in patients with knee osteoarthritis. *Arch Phys Med Rehabil*, 2010. 91(9): 1447-51.

64. Lund, H. Sondergaard, K. Zachariassen, T. Christensen, R. Bulow, P. Henriksen, M. Bartels, E.M. Danneskiold-Samsoe, B., and Bliddal, H. Learning effect of isokinetic measurements in healthy subjects, and reliability and comparability of Biodex and Lido dynamometers. *Clin Physiol Funct Imaging*, 2005. 25(2): 75-82.

65. Croisier, J.L. Factors associated with recurrent hamstring injuries. *Sports Med*, 2004. 34(10): 681-95.

66. Fitch, S., and McComas, A. Influence of human muscle length on fatigue. *J Physiol*, 1985. 362: 205-13.

67. Hunter, S.K., and Enoka, R.M. Sex differences in the fatigability of arm muscles depends on absolute force during isometric contractions. *J Appl Physiol (1985)*, 2001. 91(6): 2686-94.

68. McKenzie, D.K., and Gandevia, S.C. Influence of muscle length on human inspiratory and limb muscle endurance. *Respir Physiol*, 1987. 67(2): 171-82.

69. Clark, G.T., and Carter, M.C. Electromyographic study of human jaw-closing muscle endurance, fatigue and recovery at various isometric force levels. *Arch Oral Biol*, 1985. 30(7): 563-9.

70. Fleiss, J. The design and analysis of clinical experiments. Wiley, New York – Chichester – Brislane – Toronto – Singapore 1986, 432 S., £38.35. Biometrical Journal. 1986, New York: John Wiley Sons.

71. Lambert, C.P. Archer, R.L., and Evans, W.J. Muscle strength and fatigue during isokinetic exercise in individuals with multiple sclerosis. *Med Sci Sports Exerc*, 2001. 33(10): 1613-9.

72. Moreau, N.G. Li, L. Geaghan, J.P., and Damiano, D.L. Fatigue resistance during a voluntary performance task is associated with lower levels of mobility in cerebral palsy. *Arch Phys Med Rehabil*, 2008. 89(10): 2011-6.

73. Lopes, J.S.S. Micheletti, J.K. Machado, A.F. Souto, L.R. de Lima, H.P. Vanderlei, F.M. Junior, J.N., and Pastre, C.M. Test-retest reliability of knee extensors endurance test with elastic resistance. *PLoS One*, 2018. 13(8): e0203259.