

REDUNDANCY AND PREDICTIVE VALUE OF ISOKINETIC KNEE FATIGABILITY PARAMETERS IN HEALTHY MALES: A CROSS-SECTIONAL STUDY FROM SEDENTARY TO ELITE ATHLETES

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Abstract

BACKGROUND: Isokinetic dynamometry is widely used to assess muscle fatigability, particularly in athletes, due to its high reproducibility and sensitivity. However, the clinical and practical relevance of fatigability parameters remains debated, especially regarding their added value compared to simpler strength indicators.

Objectives: The objectives of this study were to determine (1) the redundancy of measured knee extensor fatigability parameters, (2) the feasibility of predicting them from the best repetition (BR₁), and (3) the relationship between initial strength and fatigability.

Methods: 189 healthy male volunteers (sedentary to elite athletes) performed 30 maximal concentric knee flexions extensions at 180°.s⁻¹. Pearson correlations, linear regressions, and k-fold cross-validation (k = 10) assessed parameter relationships and derived predictive equations.

Results: Very strong correlations (PCC > 0.80) linked BR₁ to most fatigability parameters, indicating high redundancy. Predictive equations based on BR₁ accurately estimated total/partial sums (R² > 0.95, ICC > 0.90). Moreover, stronger individuals exhibited steeper performance declines (PCC < -0.80 between BR₁ and slope of the regression of the performance).

Conclusions: Fatigability parameters offer limited added value, as they are highly redundant with BR₁. Simplified BR₁-based protocols suffice for clinical use, while full isokinetic testing remains essential for elite athletes or (neuro)muscular pathology requiring precision.

Keywords

Isokinetic dynamometer, fatigability, fatigability resistance evaluation protocol, transposition formulas, fatigue index, derived and measured parameters, knee joint, performance assessment

Introduction

Strength and conditioning trainer, clinicians and researchers have to frequently evaluate endurance to fatigue, i.e., termed anaerobic lactic energy system,¹ not only for sports(wo)men: to monitor training status,² to program more effectively conditioning and training,³ to validate the return to play process,^{4,5} or to appreciate the muscular characteristics of a patient with neuromuscular pathology.^{6,7} Indeed, the ability to maintain force levels despite accumulating fatigue is a major determinant of performance,⁸ as well as a characteristic of functional vulnerabilities.⁹ As defined by Bigland-Ritchie et al., fatigue refers to “any reduction in the capacity of the total neuromuscular system to generate force, regardless of the force level deployed”.¹⁰ Several methods allow for the exploration of muscle fatigability. Among these, we can mention field tests (e.g., repeated sprint tests, Wingate tests),^{11,12} surface electromyography (EMG),^{13,14} intramuscular electrical stimulation (EMS) enabling the analysis of maximal force evolution (voluntary or evoked) under fatigue conditions,¹⁵ muscle biopsies through post-exercise metabolite analysis,^{16–18} magnetic resonance imaging (MRI) or mass spectroscopy allowing e.g., the evaluation of phosphate depletion or intracellular acidosis,^{19,20} near-infrared spectroscopy (NIRS),^{14,20} and isokinetic dynamometry. However, the latter has a central role,²¹ particularly due to its high reproducibility and sensitivity^{22–25} to changes induced by training or pathology. Isokinetic testing analytical nature allows for the isolation of key muscle groups involved in critical sports movements or injury syndromes.

However, the isokinetic dynamometry use in assessing fatigability raises persistent methodological questions, particularly regarding the choice of parameters to analyze and their clinical or sporting relevance. Bosquet et al.²⁵ have shown that thirty reciprocal maximal concentric contractions appears to be the best compromise between reliability, specificity and interpretability of the data in the context of the isokinetic exploration of muscular fatigability. In this context, many clinicians and researchers base their analysis and possible implications in rehabilitation or training on fatigability derived or measured parameters. The measured parameters are the best repetition, the total and partial 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. So, the derived parameters are attractive by their theoretical ability to characterize the decrease of performance during the evaluation. Also, the literature provides a multitude of various derived parameters.^{26–35} Unfortunately, the derived parameters have been demonstrated as unusable due to clinically unacceptable reproducibility while the fatigability measured parameters can be used for assessing knee extensors (not flexors) fatigue.²²

Nevertheless, reproducibility alone is not sufficient to establish the clinical or practical utility of fatigability parameters. While numerous measured parameters are available, their selection must be guided by specific criteria. Ideally, these parameters should provide unique, nonredundant information — rather than merely replicating data that could be obtained more easily or with less physical demand on the athlete or patient. Furthermore, the clinical relevance of fatigue induction testing remains an open question: should such assessments be applied universally (e.g., to sedentary individuals, high-level athletes, etc.), or should they be reserved for targeted populations where fatigability offers distinct diagnostic or performance insights?

The primary objective of this study was to determine which fatigability measured parameters provide distinct information compared to other ones, thereby offering added clinical and research value. If redundancy was identified among these parameters, we derived predictive equations using only the most accessible or least fatiguing indicators to enable the extrapolation of all measured parameters, thereby optimizing the ecological validity of testing for the subject.

Material and methods

VOLUNTEERS

One hundred eighty-nine healthy male volunteers were included in this retrospective database study at the Motion Analysis Laboratory (LAM) of the University of Liège. Inclusion criteria were strictly defined as follows: male sex; age between 18 and 45 years; absence of any history of lower limb or spine injury; no active neuromuscular, neurological, or metabolic pathology; and no use of medications or supplements known to affect neuromuscular function, muscle metabolism, or exercise capacity. This study was conducted in conformity with ethical standards and (inter)national laws³⁶ and approved by the Ethics Committee of the University and Faculty Hospital of Liège.

Exclusion criteria systematically applied included: (1) history of significant lower limb trauma, surgery, or musculoskeletal pathology affecting the knee joint, hip, or ankle; (2) current or recent (within 6 months) spine injury or chronic spinal conditions; (3) neurological disorders potentially affecting voluntary muscle control or force production; (4) cardiovascular contraindications to maximal exercise testing; (5) use of medications or supplements affecting muscle physiology, metabolism, or central nervous system function; (6) inability to provide informed written consent; and (7) inability to understand and comply with testing procedures and safety instructions.

Medical examination and health screening were conducted by trained medical personnel and included the following components : (1) comprehensive medical history assessment, including evaluation of past medical events, surgical history, medication use, and family history of cardiovascular, neurological, or metabolic disease; (2) review of systems focusing on musculoskeletal, neurological, and cardiovascular domains; (3) vital signs measurement including resting heart rate, blood pressure, and respiratory rate, all assessed in a seated position after 5 min of rest; (4) anthropometric measurements including height (stadiometer, precision ± 0.1 cm) and body weight (calibrated scale, precision ± 0.1 kg); (5) focused physical examination of the bilateral lower limbs, specifically assessing knee joint integrity through standard orthopedic tests (Lachman test, anterior drawer test, valgus and varus stress tests), knee range of motion, muscle symmetry, and gross motor control; (6) screening for neurological deficits including cranial nerve assessment, myotatic reflexes, gross motor coordination, and sensory screening; and (7) assessment of cardiovascular fitness using the new Physical Activity Readiness Questionnaire (PAR-Q+) to identify individuals requiring additional medical clearance prior to maximal exertion testing.³⁷ All volunteers demonstrating any contraindications to maximal isokinetic testing were excluded at this stage. Those presenting with elevated blood pressure ($> 140/90$ mmHg), abnormal resting heart rate, signs of joint instability,

neurological abnormalities, or any other medical condition raising safety concerns were excluded from participation.

Participants were categorized into five activity levels based on pre-categorized database records of their self-reported weekly physical activity: sedentary/lowly active (less than 2h per week; $n = 35$), moderately active (between 2 and 6h per week; $n = 92$), active (between 6 and 10h per week; $n = 26$), very active (at least 10h per week; $n = 30$), and international-level track and field athletes (400 m sprint specialists; $n = 6$).

The age, height and body weight are shown in the table below (*Table 1*) for each subgroup and for overall population.

Table 1. Anthropometric data of volunteers (means $\pm$ standard deviation (SD)).

	Age	Height	Body weight
<i>Sedentary/lowly active</i>	24.3 ± 3.4 years	180.1 ± 6.7 cm	77.4 ± 11.3 kg
<i>Moderately active</i>	23.2 ± 4.1 years	181.7 ± 7.5 cm	77.2 ± 9.5 kg
<i>Active</i>	29.0 ± 10.7 years	180.4 ± 7.6 cm	74.7 ± 10.6 kg
<i>Very active</i>	25.3 ± 3.1 years	181.7 ± 5.1 cm	79.6 ± 12.3 kg
<i>International-level</i>	22.1 ± 3.8 years	182.3 ± 6.0 cm	72.3 ± 7.4 kg
<i>Overall</i>	25.5 ± 5.6 years	180.7 ± 6.6 cm	77.2 ± 11.1 kg

EXPERIMENTAL DESIGN

Following a thorough briefing, all volunteers signed an information and consent form. One isokinetic testing session was carried out for each participant. To avoid possible effects of residual fatigue due to recent exercises, they were asked to refrain from physical activity for forty-eight hours before the evaluation session. In order to standardize the test conditions as much as possible, they were asked: (1) to follow a stable sleep schedule in the few days before the sessions, (2) not to eat any heavy meal in the three hours preceding the test and (3) not to drink coffee, tea or any else energy drink the day of the test.³⁸

ISOKINETIC TESTING

Isokinetic evaluations were performed on a Cybex Humac CSMI (Computer Sports Medicine Inc., Stoughton, MA). This dynamometer has an excellent reliability with an Intraclass Correlation Coefficient (ICC) at least 0.93 and 0.89 respectively for Peak Moment (PM) and Maximal Work (MW).³⁹ The dominant leg, defined as the preferred kicking leg, was determined by physically observing each participant perform a ball kick. We tested only this dominant leg. The volunteer was sitting in the seat of the dynamometer, with the backrest raised at 85° to the horizontal, and was stabilized with straps at the thigh, pelvis and shoulders. The knee's axis of rotation was aligned with the dynamometer's axis of rotation by 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. Range of motion (ROM) was set to 100° with 0° corresponding to the maximum active extension. The 100° ROM was specifically chosen in accordance with the validated protocol established by Bosquet et al.²⁵ Compared to shorter protocols, this extended ROM enhances the reliability of muscle fatigue indicators. Furthermore, it offers optimal sensitivity for detecting fatigue-induced alterations while ensuring the data remains physiologically interpretable. The weight of the leg was measured and its influence on performance was automatically taken into account through the dynamometer software.

Prior to testing, volunteers were instructed to push up and pull down until the dynamometer stopped, in order to achieve a full ROM. During the evaluation, the researcher gave them special attention and consistently reminded them about this instruction. To ensure familiarization and complete the set-up, they performed two set of five submaximal but progressively intensified — from 50% to 100% — concentric contractions intensity at 120°.s⁻¹.⁴⁰ After one minute of rest, participants completed three reciprocal concentric submaximal contractions at 180°.s⁻¹. After again one minute of rest, they underwent the formal test, which consisted of thirty consecutive maximal reciprocal concentric contractions at the angular velocity of 180°.s⁻¹.²⁵ Each participant was 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 them to develop highest peak moment and maximal work at each repetition, the researcher verbally encouraged them throughout the testing session.⁴¹

DATA ANALYSIS

PM (in N·m) and MW (in J) were computed for each repetition. 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 torque produced during a given contraction while the MW is the area under the torque curve.^{25,42} As reported by Manca et al.,⁴³ Morrissey⁴⁴ explains that an only PM-based analysis may induce an overestimation of the muscular moment output. Therefore, several researchers^{43,45} consider that the MW may serve as a better muscle function indicator than PM, especially in the rehabilitation process and in frail populations.⁴⁶

As previously demonstrated, the derived fatigability parameters have an insufficient intra-dynamometer reproducibility for use in clinical and/or research context and therefore they were excluded from the present construct validity analyses.²² For the extensors, eleven measured parameters were selected (*Table 2*), based on a prior reproducibility study.²² For the flexors, although fatigability parameters were analyzed, they are not considered for the main results due to their insufficient inter-session reproducibility, as demonstrated in the same preliminary analysis.²² However, to ensure full transparency and provide complete information to the reader, all correlation and regression data concerning the flexors have been made available in the Supplementary Materials (*Supplementary Table 3 to 6*).

Table 2. Knee measured fatigability parameters with $BR_x = x^{th}$ Best Repetition; $\Sigma [Rx:Ry]$ = cumulated performance from x^{th} to y^{th} repetition.

Measured parameters for knee extensors			
BR_1	$\Sigma [R1:R30]$	$\Sigma [R1:R10]$	$\Sigma [R11:R20]$
$\Sigma [R21:R30]$	$\Sigma [R1:R5]$	$\Sigma [R6:R10]$	$\Sigma [R11:R15]$
$\Sigma [R16:R20]$	$\Sigma [R21:R25]$	$\Sigma [R26:R30]$	

Predictive equations. As mentioned previously, one of the objectives of this study was to derive predictive equations using only the most accessible or least fatiguing indicators to enable the extrapolation of all measured parameters if redundancy was identified among these parameters. To achieve this, the estimated total and partials sums values ($\Sigma' [Rx:Ry]$) were calculated, from k-folds validation ($k = 10$) process, by a linear first-degree equation (" $y = a.x$ " or, in other words $\Sigma' [Rx:Ry] = a.BR_1$ per example). a , coefficient of x , has been determined by the method of the linear least squares which consist in minimizing the differences between the $\Sigma [Rx:Ry]$ and $\Sigma' [Rx:Ry]$ values. The absence of outliers was verified using the boxplot method.⁴⁷ We calculate a independently for PM and MW datasets.

STATISTICAL ANALYSIS

Global analysis. Normal Gaussian distribution of the data was verified by the Shapiro-Wilk test. Statistical significance was set at p-value < 0.05 level for all analysis and confidence intervals was fixed to 95%. All calculations were made with Statistica 10 (Statsofts, Tulsa, OK), MedCalc 13.3.3 (MedCalc Software, Ostend, Belgium) and Excel 2016 (Microsoft, Redmond, WA).

Construct validity and parameter redundancy was measured by the Pearson's r product-moment correlation coefficient (PCC) and linear regression analyses with coefficients of determination associated (R^2) between fatigability measured parameters (between best repetition (BR_1) and total sum ($\Sigma [R1:R30]$) for example). These analyses provide evidence regarding the internal structure and construct validity of the fatigability measures, by quantifying the extent to which additional parameters reflect the same underlying performance construct as BR_1 .

The PCC corresponds to the covariance of the two variables divided by the product of their standard deviations. "These correlations quantify the direction and the strength of the relationship between the scores by estimating their linear relationship, and lies between +1 and -1".⁴⁸ Threshold absolute values for PCC statistics were < 0.20, 0.20, 0.60 and 0.80 for weak, moderate, strong and very strong, respectively.⁴⁹

Estimated values. This approach was performed by randomly dividing the set of observation values into k nonoverlapping folds of approximately equal size. The first fold is treated as a validation set, and the model is fit to the remanding k-1 folds (training data).

The ability of the fitted linear models to reproduce the actual observed values was quantified using the Standard Error of Measurements (SEM)^{50,51} and ICC_{2,1}.⁵² In this context, these indices were interpreted as measures of absolute and relative agreement between predicted and observed scores,

providing additional evidence for the validity of using BR1 as a proxy for cumulative performance. Equation 1 was taken as the criterion for acceptable absolute compatibility.^{53–58}

$$SEM \leq \frac{SD}{2} \quad (1)$$

The ICC (2,1) (single measures), which assesses rating reliability that “represents the proportion of variance in a set of scores that is attributable to the true score variance”.⁵² An ICC higher than 0.90 is considered as excellent, between 0.70 and 0.89 as high and between 0.50 and 0.69 as moderate.^{25,59} Currier⁶⁰ and Saenz et al.⁶¹ 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.

Results

The correlation between BR_1 and $\Sigma [R1:R30]$ was very strong for the PM ($r = 0.90$ [0.87, 0.93], $p < 0.001$), as illustrated in *Figure 1*. As detailed in *Table 3*, this very strong correlation was observed for both the overall population and the subgroups, as well as for the MW.

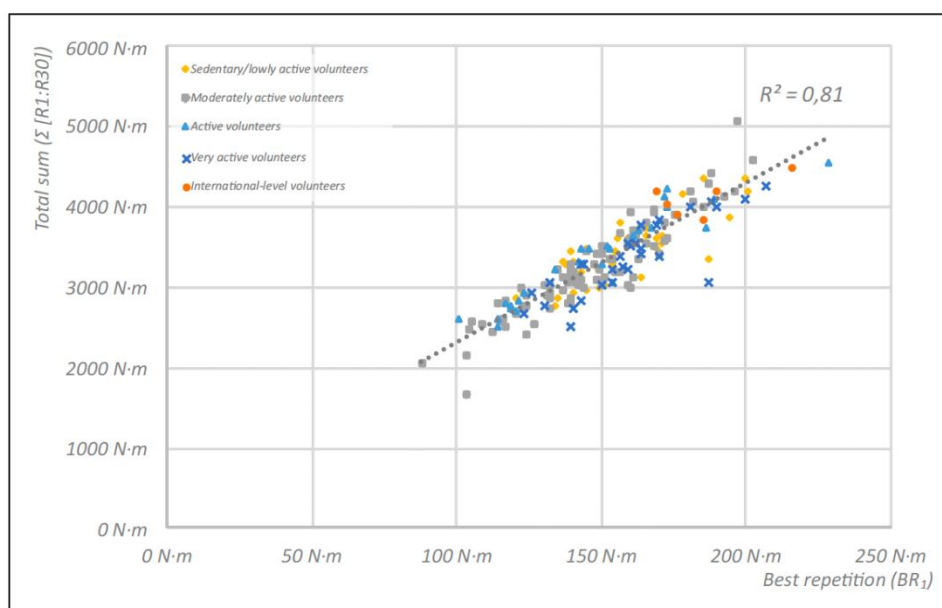


Figure 1. Relationship between best repetition (BR1) and the total sum ($\Sigma [R1:R30]$) (Peak Moment) for all subgroup and linear regression (dotted line) between BR1 and $\Sigma [R1:R30]$ for overall population.

Furthermore, the correlation data between BR_1 and partial sums (by five or ten repetitions) for both PM and MW are presented in *Table 4*. These correlations were very strong for the initial partial sums ($\Sigma [R1:R10]$, $\Sigma [R11:R20]$, $\Sigma [R1:R5]$, $\Sigma [R6:R10]$, and $\Sigma [R11:R15]$) and strong for the final ones ($\Sigma [R21:R30]$, $\Sigma [R16:R20]$, $\Sigma [R21:R25]$, and $\Sigma [R26:R30]$).

Table 4. Pearson's r with CI 95% and p -value associated between extensors PM-based and MW-based BR_1 and fatigability parameters with $BR_x = x^{th}$ Best Repetition and $\Sigma [R_x:R_y]$ = cumulated performance from x^{th} to y^{th} repetition.

Peak moment - extensors											
	$\Sigma [R1:R30]$	$\Sigma [R1:R10]$	$\Sigma [R11:R20]$	$\Sigma [R21:R30]$	$\Sigma [R1:R5]$	$\Sigma [R6:R10]$	$\Sigma [R11:R15]$	$\Sigma [R16:R20]$	$\Sigma [R21:R25]$	$\Sigma [R26:R30]$	Slope
BR_1	0.90 [0.87,0.92] $p < 0.001$	0.98 [0.97,0.98] $p < 0.001$	0.84 [0.80,0.88] $p < 0.001$	0.71 [0.63,0.77] $p < 0.001$	0.98 [0.97,0.98] $p < 0.001$	0.93 [0.91,0.95] $p < 0.001$	0.87 [0.83,0.90] $p < 0.001$	0.80 [0.74,0.85] $p < 0.001$	0.72 [0.65,0.79] $p < 0.001$	0.67 [0.58,0.74] $p < 0.001$	-0.81 [-0.85,-0.75] $p < 0.001$
Maximal work - Extensors											
	$\Sigma [R1:R30]$	$\Sigma [R1:R10]$	$\Sigma [R11:R20]$	$\Sigma [R21:R30]$	$\Sigma [R1:R5]$	$\Sigma [R6:R10]$	$\Sigma [R11:R15]$	$\Sigma [R16:R20]$	$\Sigma [R21:R25]$	$\Sigma [R26:R30]$	Slope
BR_1	0.90 [0.87,0.93] $p < 0.001$	0.98 [0.97,0.98] $p < 0.001$	0.84 [0.80,0.88] $p < 0.001$	0.68 [0.60,0.76] $p < 0.001$	0.98 [0.97,0.98] $p < 0.001$	0.93 [0.91,0.95] $p < 0.001$	0.87 [0.84,0.91] $p < 0.001$	0.79 [0.73,0.84] $p < 0.001$	0.70 [0.63,0.77] $p < 0.001$	0.64 [0.55,0.72] $p < 0.001$	-0.83 [-0.89,-0.76] $p < 0.001$

To avoid any mathematical coupling bias, particularly for shorter intervals where BR_1 might have a proportionally larger impact, correlations were also performed excluding BR_1 from the respective sums. The relationships remained very strong and significant when BR_1 was excluded from the total sum ($r = 0.89$ [0.86, 0.92] with $p < 0.001$), the first ten repetitions ($r = 0.97$ [0.96, 0.98] with $p < 0.001$), and the first five repetitions ($r = 0.97$ [0.96, 0.98] with $p < 0.001$).

Finally, all possible combinations of correlations between all fatigue parameters for the overall sample are presented in *Supplementary Table 1*.

Another finding is that the very strong negative correlation and statistically significant between BR_1 and slope of the linear regression of the performance (whether PM or MW) with Pearson's r lower than -0.80 ($r = -0.81$ [-0.85, -0.75] with $p < 0.001$) (see *Figure 2*).

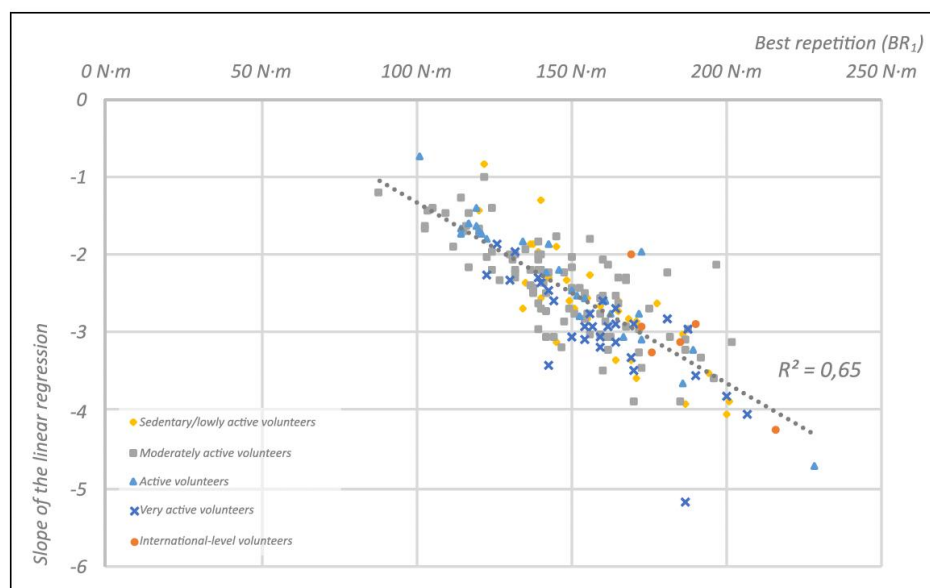


Figure 2. Relationship between best repetition (BR_1) and the slope of the linear regression of performance (Peak Moment) for all subgroup and linear regression (dotted line) between BR_1 and slope for overall population.

The formulas for calculating $\Sigma' [R_x:R_y]$ (with coefficient of determination, goodness-of-fit of linear model) are provided in *Supplementary Table 2*. The k-folds validation data ($ICC_{2,1}$, Spearman's r & SEM) between estimated and measured total and partials sums are presented in *Table 5*. For both PM and MW, the ICC values between estimated and observed parameters were excellent for the total sum ($\Sigma' [R1:R30]$) and the initial partial sums ($\Sigma' [R1:R10]$, $\Sigma' [R1:R5]$ and $\Sigma' [R6:R10]$). For the later partial sums, ICC values were lower, but still high. The lowest values observed for $\Sigma' [R26:R30]$ ($ICC_{2,1} = 0.70 \pm 0.12$). Furthermore, the SEM values met the criterion for acceptable absolute compatibility

(Equation 1) for the total sum ($\Sigma' [R1:R30]$) and the partial sums with exception for $\Sigma' [R21:R30]$ (for MW), $\Sigma' [R21:R25]$ (for MW) and $\Sigma' [R26:R30]$ (for PM and MW).

Table 5. Mean $\pm$ SD of k-folds validation ($k = 10$) ICC_{2,1}, Spearman's r & SEM between estimated (by a linear first-degree equation based on BR1) and measured total and partials sums with $BR_x = x^{th}$ Best Repetition and $\Sigma [R_x:R_y]$ = cumulated performance from x^{th} to y repetition. When the SEM meets the criterion for acceptable absolute compatibility (see Equation 1), the SEM's value is underlined.

		$\Sigma' [R1:R30]$	$\Sigma' [R1:R10]$	$\Sigma' [R11:R20]$	$\Sigma' [R21:R30]$	$\Sigma' [R1:R5]$	$\Sigma' [R6:R10]$	$\Sigma' [R11:R15]$	$\Sigma' [R16:R20]$	$\Sigma' [R21:R25]$	$\Sigma' [R26:R30]$
Peak Moment - Extensors	ICC _{2,1}	0.91 $\pm$ 0.05	0.98 $\pm$ 0.01	0.86 $\pm$ 0.06	0.73 $\pm$ 0.13	0.98 $\pm$ 0.01	0.94 $\pm$ 0.03	0.88 $\pm$ 0.04	0.82 $\pm$ 0.08	0.75 $\pm$ 0.15	0.70 $\pm$ 0.12
	R Spearman	0.90 $\pm$ 0.06	0.98 $\pm$ 0.01	0.86 $\pm$ 0.06	0.74 $\pm$ 0.09	0.98 $\pm$ 0.01	0.93 $\pm$ 0.03	0.88 $\pm$ 0.04	0.81 $\pm$ 0.08	0.76 $\pm$ 0.10	0.69 $\pm$ 0.12
	SEM (N-m)	155.7 $\pm$ 35.4	31.1 $\pm$ 7.2	66.9 $\pm$ 13.0	72.7 $\pm$ 15.8	15.3 $\pm$ 3.9	26.4 $\pm$ 4.4	32.4 $\pm$ 5.1	35.9 $\pm$ 8.4	37.4 $\pm$ 10.2	36.8 $\pm$ 6.4
Maximal Work - Extensors	ICC _{2,1}	0.91 $\pm$ 0.05	0.98 $\pm$ 0.01	0.85 $\pm$ 0.05	0.70 $\pm$ 0.13	0.98 $\pm$ 0.01	0.94 $\pm$ 0.03	0.88 $\pm$ 0.04	0.81 $\pm$ 0.08	0.72 $\pm$ 0.14	0.70 $\pm$ 0.12
	R Spearman	0.90 $\pm$ 0.06	0.98 $\pm$ 0.01	0.84 $\pm$ 0.06	0.70 $\pm$ 0.10	0.98 $\pm$ 0.01	0.93 $\pm$ 0.03	0.87 $\pm$ 0.05	0.80 $\pm$ 0.09	0.73 $\pm$ 0.11	0.66 $\pm$ 0.10
	SEM (J)	180.1 $\pm$ 41.2	34.4 $\pm$ 8.3	77.8 $\pm$ 15.7	86.1 $\pm$ 18.5	18.6 $\pm$ 4.5	30.1 $\pm$ 6.1	37.2 $\pm$ 6.2	42.3 $\pm$ 10.0	44.6 $\pm$ 12.0	43.2 $\pm$ 7.5

Discussion

To our knowledge, the added value of isokinetic fatigability parameters has not been ever studied while they are frequently used.^{26–35} This prompted us to investigate whether the multiple fatigability parameters commonly measured in isokinetic testing provide complementary information, or if some are redundant. We hypothesized that identifying distinct parameters and establishing predictive equations based on the most practical and least burdensome indicators could streamline clinical assessment while preserving diagnostic accuracy.

To be considered as bringing added value, a parameter cannot provide redundant information compared to another one, it must produce different information. This relates directly to construct validity: if multiple parameters are highly correlated, they likely measure the same underlying construct rather than distinct facets of fatigue. With this consideration in mind, the fatigability measured parameters do not seem to provide a lot of complementary information compared to the BR₁. Except for the last partials sums by five and ten repetitions ($\Sigma [R21:R25]$, $\Sigma [R26:R30]$ & $\Sigma [R21:R30]$), the correlation between fatigability measured parameters and the best repetition is at least high and acceptable for clinical work which means that their values are linked by a linear relationship. As explained by Coutts,⁶² “an all too common trap (...) is to get caught up in collecting information - then trawl through reams of numbers in an attempt to find relationships of interest (that may not even exist) - without being able to provide the coach or athlete with any meaningful information”. For example, the estimated values of total sum ($\Sigma' [R1:R30]$) from the best repetition by the linear first-degree equation are extremely close to measured values of total sum ($\Sigma [R1:R30]$) since their absolute (SEM) and relative (ICC) agreement have been shown to be excellent,^{25,53–61} so in this case, the predictive equations should be used to obtain the values' extrapolation.

However, it should be noted that the agreement between the best repetition and the partial sums tends to decrease as the isokinetic test progresses. Indeed, as previously demonstrated, 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.²² Moreover, the poor reproducibility of the (relative and absolute) variability means that this is not an intrinsic characteristic of the subjects or the evaluation but a factor inherent of the fatigue induced by the testing session.²² While the correlation of later partial sums remains high enough (or nearly so) for certain populations, this slight loss of precision is acceptable in clinical or non-sporting contexts—such as for sedentary individuals or

patients—where the primary goal is often a general assessment (e.g., detecting major asymmetries, monitoring rehabilitation progress, or screening for functional limitations). In these cases, a broad estimation of fatigability may suffice to guide therapeutic decisions or basic physical activity recommendations, without requiring the granularity needed for performance optimization. By contrast, for high-level athletes, where marginal gains in strength, endurance, or recovery can significantly impact performance,^{63,64} a complete isokinetic exploration of knee muscular fatigability remains essential.⁶⁵ Higher precision allows for fine-tuned adjustments in training programs, injury prevention strategies, or return-to-sport protocols, where even minor variations in fatigability metrics may be critical.⁶⁶

Another main finding that emerged from our study is that the slope of the linear regression of the PM and MW is very strongly negatively correlated to the best performance. In other words, the volunteers with the best qualities of force at $180^{\circ} \cdot s^{-1}$ are those with the lowest relative qualities of endurance to fatigue. This finding is in adequacy with the results of Nordlund et al.⁶⁷ who highlighted that peripheral fatigue could be explained by 55% by the maximal voluntary plantar flexor torque during the first bout of exercise and Hunter et al.⁶⁸ who pointed out that “stronger individuals had a briefer endurance time and that this relation was exponential for both the elbow flexors and the hand muscle”. But, at our knowledge, our study is the first to demonstrate this for the knee on so many volunteers. It is important to note, however, that the strongest volunteers, although having lower relative qualities of endurance to fatigue, have partial sums by five and ten repetitions higher than other volunteers at the end of the evaluation ($\Sigma [R21:R25]$, $\Sigma [R26:R30]$ & $\Sigma [R21:R30]$).

The redundancy between BR_1 and fatigability parameters obscures a fundamental physiological reality: while global performance ($\Sigma [R1:R30]$) is strongly correlated with the best repetition, subjects with a high BR_1 maintain absolutely higher force levels at every repetition—even during the decline phase—compared to weaker subjects. This phenomenon could be attributed to muscle phenotype composition: individuals with high BR_1 typically exhibit a greater proportion of type IIx/IIa fibers, which generate high force output due to larger cross-sectional areas and rapid ATPase activity but rely heavily on anaerobic metabolism (glycolysis and phosphagen system).^{69,70} While this metabolic profile enables high peak force, it also leads to rapid accumulation of inorganic phosphate (Pi) — rather than lactate or H^+ — primarily drives fatigue by reducing crossbridge force and SR Ca^{2+} release, accelerating performance decline across repetitions.⁷¹ Thus, the steeper negative slope observed in stronger subjects does not indicate absolute performance collapse but rather a relative decline from a much higher baseline—one that remains superior to that of weaker individuals, even at the protocol’s end. From a neurophysiological perspective, this heightened fatigability in stronger subjects could further explained by early reflex inhibition mediated by group III and IV afferents muscle (nociceptors and metaboreceptors). The rapid metabolite buildup in type II fibers, combined with intracellular disturbances (acidosis, phosphocreatine depletion), activates these receptors, which transmit inhibitory signals to the spinal cord and motor cortex. This negative feedback progressively reduces central neural drive, limiting motor unit recruitment and contributing to the observed decline.^{72,73} Conversely, weaker subjects—whose oxidative metabolism (type I fibers) predominates^{69,70}—generate fewer fatigue inducing metabolites and thus experience less central inhibition, resulting in a shallower performance slope. Nevertheless, despite this greater relative fatigability in stronger individuals, their absolute advantage persists: even after 30 repetitions, their residual force (e.g., $\Sigma [R26:R30]$) remains

higher than that of weaker subjects. This confirms that initial capacity (BR1) largely determines the overall performance ceiling, regardless of the decay rate.

Although the influence of training level was not statistically evaluated, visual assessment of Figure 1 and Table 3 suggests a homogeneous distribution in performance across the cohort, regardless of physical activity levels (except for international-level track and field athletes). This observation supports our phenotype composition hypothesis while acknowledging training level as a potential bias.

Table 3. Mean $\pm$ SD of best repetition and total sum with correlation's data (Pearson's r with CI 95% and p -value associated) between BR₁ and Σ [R1:R30] for each subgroup and overall population.

	Peak moment - extensors			Maximal work - extensors		
	BR ₁ (N·m)	Σ [R1:R30] (N·m)	Pearson's r [CI 95%]	BR ₁	Σ [R1:R30]	Pearson's r [CI 95%]
Sedentary/lowly active volunteers	147.2 $\pm$ 23.8	3253.3 $\pm$ 574.3	0.83 [0.69,0.91] p -value < 0.001	172.4 $\pm$ 27.6 J	3761.5 $\pm$ 634.0 J	0.86 [0.74,0.93] p -value < 0.001
Moderately active volunteers	156.1 $\pm$ 20.8	3422.0 $\pm$ 424.4	0.93 [0.90,0.95] p -value < 0.001	183.1 $\pm$ 28.1 J	3957.8 $\pm$ 530.7 J	0.93 [0.89,0.95] p -value < 0.001
Active volunteers	147.5 $\pm$ 29.5	3354.2 $\pm$ 572.6	0.95 [0.88,0.98] p -value < 0.001	171.9 $\pm$ 33.7 J	3879.0 $\pm$ 641.3 J	0.94 [0.87,0.97] p -value < 0.001
Very active volunteers	159.5 $\pm$ 21.2	3371.6 $\pm$ 464.5	0.86 [0.72,0.93] p -value < 0.001	188.2 $\pm$ 26.2 J	3907.1 $\pm$ 546.8 J	0.88 [0.77,0.94] p -value < 0.001
International-level volunteers	184.8 $\pm$ 17.1	4110.8 $\pm$ 226.2	0.75 [-0.17,0.97] p -value = 0.066	200.0 $\pm$ 35.0 J	4456.2 $\pm$ 603.5 J	0.95 [0.61,0.99] p -value < 0.001
Overall population	152.0 $\pm$ 24.6	3344.4 $\pm$ 542.7	0.90 [0.87,0.92] p -value < 0.001	177.7 $\pm$ 29.3 J	3859.2 $\pm$ 611.8 J	0.90 [0.88,0.93] p -value < 0.001

The population was a limitation of this study: the findings of the present study, as a precautionary measure, should not be generalized to other populations than healthy male, from sedentary to very active level, volunteers. Another limitation was that this study focused only on the knee joint. Since fatigability resistance assessments are not limited to the knee, it would be highly relevant to evaluate the added value of fatigability parameters from other joints — particularly given their role in data filtering.

Conclusion

Even if the use of some knee measured parameters do not represent an added value, except in some very specific contexts, such a protocol of thirty knee reciprocal maximal isokinetic concentric contractions is very useful due to its sports specificity and its usefulness in the context of (neuro)muscular pathology.^{25,74–77} However, it seems important to continue the search for relevant and meaningfully fatigability parameters allowing a fine analysis of this kind of test.

Practical applications

- The correlation between fatigability measured parameters and the best repetition is at least very strong.
- The added value of isokinetic fatigability measured parameters is weak.

- The volunteers with the best qualities of force at $180^{\circ} \cdot s^{-1}$ are those with the lowest relative qualities of isokinetic endurance to fatigue.
- Our “ $y = a \cdot x$ ” first-degree equations are perfectly adapted for the calculation of estimated values of the total sum.

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Supplemental material

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