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RELIABILITY OF KNEE MUSCLE STRENGTH AND FATIGUE MEASUREMENTS

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Abstract. Different methods for assessing knee muscle strength and fatigue have been developed in recent years, and further methodological research is necessary in order to find feasible methods for use in various population groups. We aimed at investigating the intra- and inter-rater reliability of maximal knee muscle strength and fatigue measurements in healthy subjects. Thirty subjects, 13 men and 17 women, participated in the study. Three repeated assessments with one-week intervals were performed. Maximal isometric torque (Nm) of 5 s and fatigability of knee extensors and flexors during maximal isometric contractions of 30 s were assessed with a knee dynamometer. The reliability of three FATigue Indices ($FATI_1$,$FATI_2$ and $FATI_3$) was evaluated. The three fatigue indices are all based on the calculation of the Area Under the Force vs. time Curve (AUFC). In $FATI_1$ the calculation is based on the entire contraction period 0 to 30 s; $FATI_2$ is a modified version of $FATI_1$, where the first 5 s period is omitted from the calculation; and in $FATI_3$ the highest mean value during the period 0–5 s serves as the Time Point of Maximum (TPM) value of the muscle torque. The inter-rater reliability coefficients (Intraclass Correlation Coefficient, ICC) of the isometric extension and flexion torques were 0.97-0.99 and the intra-rater reliability coefficients were 0.97-0.98, respectively. The inter-rater reliability coefficients (ICC) of the fatigability assessments were 0.79-0.87 for $FATI_1$, 0.78-0.80 for $FATI_2$ and 0.80 - 0.88 for $FATI_3$, and the inter-rater reliability coefficients were 0.70-0.84 for $FATI_1$, 0.55-0.56 for $FATI_2$ and 0.73-0.82 for $FATI_3$. The highest level of fatigability was observed in $FATI_3$. Maximal isometric flexion torque correlated with $FATI_1$ in flexion ($r=-0.45$, $p<0.05$) and $FATI_3$ in flexion ($r=-0.46$, $p<0.05$). Isometric torque of knee extensors and flexors can be reliably measured with a knee dynamometer in healthy middle-aged subjects. All fatigue indices were reliable in test-retest assessments, and the indices $FATI_1$ and $FATI_3$ were also reliable in inter-rater assessments.

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Introduction

Muscular fatigue can be defined as an exercise-induced decline in the ability of muscle to exert the maximal force [10]. Muscular fatigue may be caused by peripheral changes at the muscle level, and also that the central nervous system fails to drive the motoneurons in an adequate way [11]. Noakes [17] listed in his review five possible causes for muscular fatigue: decreased cardiovascular capacity, decreased energy supply, impaired muscle recruitment, poor biomechanical conditions and decreased motivation.

Different types of fatigue indices have been developed to quantify fatigue, both during a set of repetitive muscle contractions [14,16,25] and during a sustained muscle contraction [5,7,22]. For assessment of fatigability during a sustained muscle contraction, the simplest method is to compare the maximal voluntary torque at the beginning and at the end of the performance [16]. Using this method in healthy subjects, the Intraclass Correlation Coefficient (ICC) was 0.55 [22]. Fatigue indices based on the Area Under Force vs. time Curve (AUFC) during the entire contraction period were presented by Djaldetti *et al.* [7] and Schwid *et al.* [22] with ICC of 0.48 and 0.52, respectively. Another fatigue index based on the AUFC, presented recently by Surakka *et al.* [24] showed high reliability in MS patients (ICC 0.68-0.86).

Strength of the knee extensors and flexors has been measured using hand-held and stationary dynamometers [1,2,20]. The stationary knee muscle dynamometer has shown to be more reliable in assessing knee muscle strength than hand-held dynamometer [1,9,26].

The purpose of this study was to examine and compare, in healthy middle-aged subjects, the intra-rater and inter-rater reliabilities of three fatigue indices based on AUFC during 30 s of sustained muscle contraction in knee muscle extension and flexion. Also, the reliability of isometric knee muscle strength measurement with a stationary dynamometer was assessed.

Materials and Methods

Thirty healthy volunteers (13 men and 17 women) (Table 1) were recruited from the staff of a Rehabilitation and Research Centre. Subjects were screened for cardiovascular, neurological and musculoskeletal diseases. The Ethical Committee of the South-Western Finland District of Health Care approved the study. All subjects gave their written informed consent for the participation in the study.

Table 1
Baseline characteristics and isometric torque measures of the subjects

Variable	Subjects (n=30)
Gender, female/male (n)	17/13
Age, yrs (mean±SD)	43±7
Height, cm (mean±SD)	173±11
Weight, kg (mean±SD)	73±14
Employed (n)	29
Unemployed, retired or on sick-leave (n)	1
Physical activity at leisure (n)	
little	2
some	17
plenty	11
Present sports activity (n)	25
Previous sports activity (n)	24
Isometric torque (Nm, mean±SD):	
Right knee extensor	167±63
Left knee extensor	159±66
Right knee flexor	88±29
Left knee flexor	85±27

Measurements: Knee flexor and extensor isometric strength and static fatigue were measured by a stationary knee extensor dynamometer (HUR®, Kokkola, Finland). The dynamometer uses a hydraulically powered lever arm that measures the isometric contraction of knee extensor and flexor muscles (Fig. 1). The measurements were repeated three times at intervals of one week. The repeated measurements were performed at the same time of the day and the measurement protocol was always the same. The two investigators, both with two years' experience in the use of the dynamometer, conducted all the tests. The investigators were not blinded.

Fig. 1
The knee flexor and extensor isometric strength and static fatigue were measured by a knee extensor dynamometer

Measurement of maximal 5 s isometric knee extension and flexion torque (Nm): The subject was sitting on a chair, keeping hands on the handles on both sides. In extension, the knee angle was 140° (180° refers to full extension) and the hip angle was 110°, and in flexion, the knee angle was 120° and the hip angle was 110°. The subject was instructed to exert maximal extension and flexion torque and to maintain it for 5 s. Two trials were measured for both legs with 2 min of rest between. The measurements started always with right leg and with extension. The maximal isometric knee extension and flexion torque was recorded as the mean value of 1 s at 200 Hz.

Measurement of fatigue in 30 s sustained knee extension and flexion: Sitting as described above, the subject was instructed to exert maximal extension and flexion torque and to maintain it for 30 s. The torque signal was recorded on a computer, and used in the calculation of the FATigue Indices (FATI). The measurement was performed once for both legs, starting with the right leg and with at least 2 min of rest between.

Fatigue indices: **Fatigue Index $FATI_1$** (Fig. 2a) was developed by Djaldetti *et al.* [7]. The calculation of $FATI_1$ is based on the Area Under the Force vs. time Curve (AUFC) for the entire contraction period 0 to 30 s. The area under the actual force-time curve during the 30 s measurement is divided by the hypothetical AUFC in which it is assumed that the maximal initial force is maintained through the whole 30 s period.
$FATI_1$: 100% x [1-($AUFC_{0-30}$/($F_{max\ 0-5}$ x 30))]

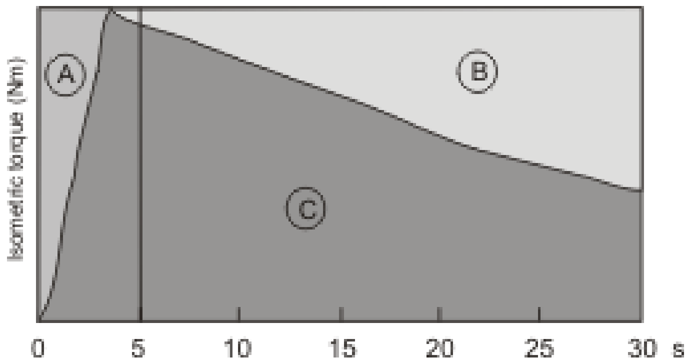

Fig. 2a
The fatigue index $FATI_1$. Hypothetical torque (Nm) versus time (s) curve during an isometric contraction sustained for 30 seconds. Calculation of fatigue index is based on the area under the curve for the entire contraction period of 30 s: C/A+B+C

Fatigue Index $FATI_2$ (Fig. 2b) is a modified version of $FATI_1$ [22] in which the first 5 s period is omitted in the index calculation. The AUFC for the period from 5 to 30 s of the sustained contraction is divided by the hypothetical AUFC in which it is assumed that the same maximal force achieved during the first 5 s is maintained through the period from 5 to 30 s.
$FATI_2$: 100% x [1-($AUFC_{5-30}$/($F_{max\ 0-5}$ x 25))]

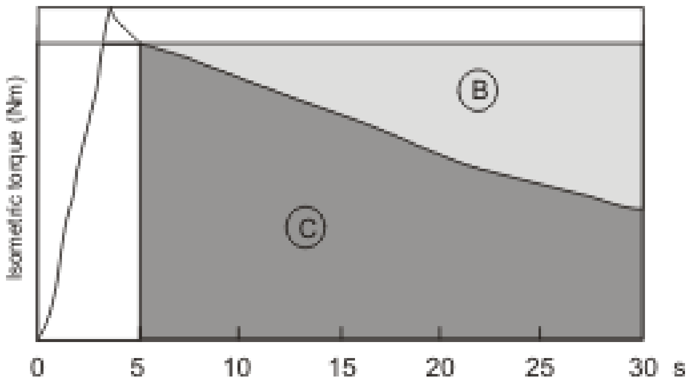

Fig. 2b
The fatigue index $FATI_2$. Hypothetical torque (Nm) versus time (s) curve during an isometric contraction sustained for 30 seconds. Calculation of fatigue index is based on the area under the curve, based on time period of 5 –30 s. The first 5 s is omitted from the fatigue calculation: B/B+C

Fatigue Index $FATI_3$ (Fig. 2c) is developed by Surakka *et al.* [24]. The highest mean value during the period from 0 to 5 s serves as the Time Point of Maximum (TPM) value of the muscle torque. The AUFC calculation starts from the TPM. The AUFC from this point to the end of the contraction (30 s) is divided with the hypothetical AUFC in which it is assumed that the same maximal force is maintained until the end of the 30 s.
$FATI_3$: 100% x [1-(AUFC $_{TPM-30}$/ (F $_{max\ 0-5}$ x(TPM-30)]

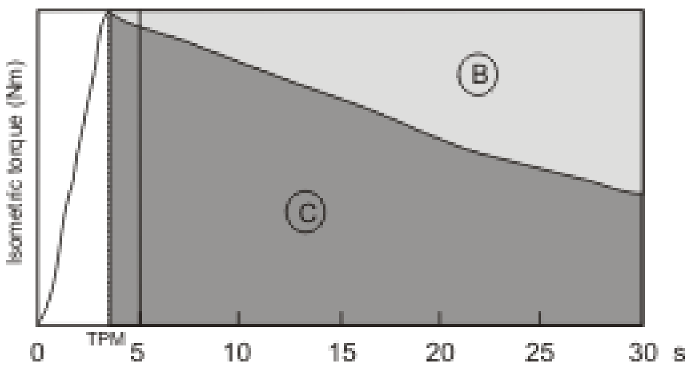

Fig. 2c
The fatigue index $FATI_3$. Hypothetical torque (Nm) versus time (s) curve during an isometric contraction sustained for 30 seconds. The change in torque is calculated

from the Time Point of Maximum value of the muscle torque (TPM) to the end of the 30 s fatigue measurement. The Fatigue Index is calculated on the basis of the areas B and C. TPM – 30 s: C/B+C

Statistical analysis: Intraclass Correlation Coefficients (ICC) were calculated for the mean torque value of both legs in extension and flexion to test the reproducibility of the measurement (excellent >0.75, good =0.4-0.75 [8]. Repeatability within the motor fatigue indices and the difference between them were assessed by repeated analysis of variance. The Bland-Altman [6] method was applied to determine the limits of agreement, with 95% CIs, between $FATI_1$, $FATI_2$ and $FATI_3$. The mean torque (Nm) of/at 1 s intervals from the TPM to the end of the measurement (30 s) was calculated and visualised in the torque/force vs. time curve. Spearman’s correlation coefficient was used to describe the association between the maximal isometric torque and the fatigue indices. SAS software version 8.2 (Cary, Indiana, USA) was used for all calculations.

Results

Maximal isometric torque. The mean isometric torque for all subjects (at baseline) was 167±63 Nm for right and 159±66 Nm for left knee extensors, and 88±29 for right and 85±25 for left knee flexors (Table 1). The intra-rater reliability (ICC) in isometric torque was 0.98 in extension and 0.97 in flexion, and the inter-rater reliability (ICC) 0.99 and 0.97, respectively.

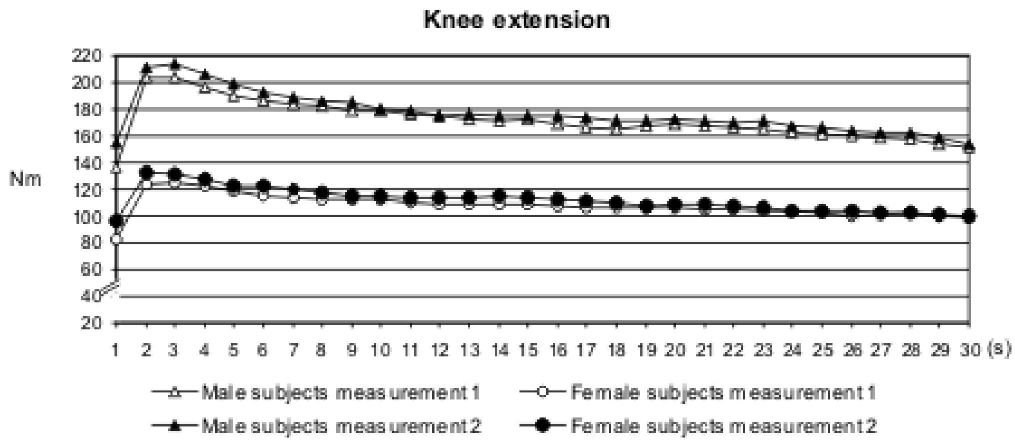

Fig. 3a

Mean torque (Nm) versus time (s) during the 30 seconds fatigue measurements 1 and 2 in knee extension in men and women. Plotted with 1 seconds intervals to the end of the 30 s recording.

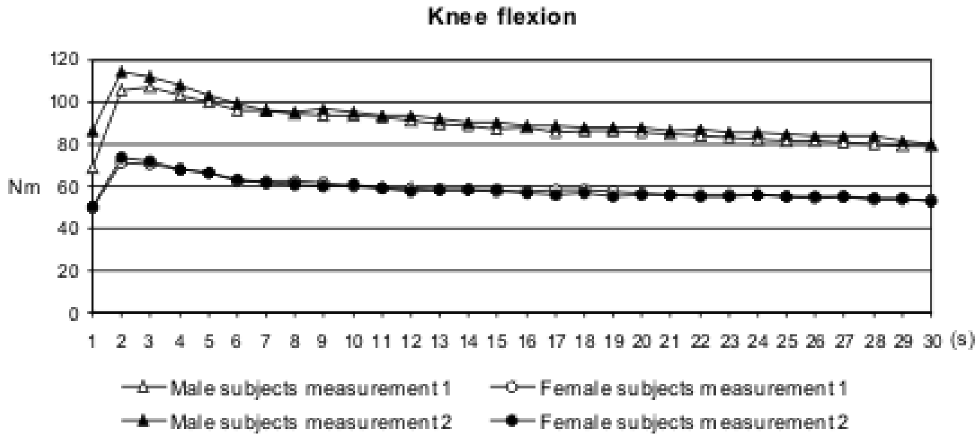

Fig. 3b
Mean torque (Nm) versus time (s) during the 30 seconds fatigue measurements 1 and 2 in knee flexion in men and women. Plotted with 1 seconds intervals to the end of the 30 s recording

Table 2
Intra- and inter-rater Intraclass Correlation Coefficients (ICC) of Fatigue Indices $FATI_1$, $FATI_2$, and $FATI_3$. Reliability is calculated as the mean value of knee extensors and flexors (both legs)

		Fatigue Index (%)	
Muscle		Intra-rater ICC (n=30)	Inter-rater ICC (n=30)
Knee extensors	$FATI_1$	0.87	0.70
Knee extensors	$FATI_2$	0.80	0.56
Knee extensors	$FATI_3$	0.88	0.73
Knee flexors	$FATI_1$	• 0.79	0.84
Knee flexors	$FATI_2$	• 0.78	0.55
Knee flexors	$FATI_3$	• 0.80	0.82

• Note: one subject was excluded from the data analysis; the flexion performance failed because of sudden pain in left flexor muscles

Reliability of 30 s fatigability measurements. The test-retest torque vs. time curves are visualised in Figures 3a and 3b for men and women, respectively.

The intra- and inter-rater reliabilities (ICC) are presented in Table 2, and the fatigue indices ($FATI_1$, $FATI_2$ and $FATI_3$) of the first measurement are shown in Table 3.

Table 3
The fatigue indices ($FATI_1$, $FATI_2$ and $FATI_3$) of the first measurement, expressed as mean±SD

	Subjects (n=30)
Right knee extensor (%, mean±SD)	
$FATI_1$	20±7
$FATI_2$	10±8
$FATI_3$	20±7
Left knee extensor (%, mean±SD)	
$FATI_1$	22±11
$FATI_2$	9±8
$FATI_3$	21±12
Right knee flexor (%, mean±SD)	
$FATI_1$	22±7
$FATI_2$	10±7
$FATI_3$	21±7
Left knee flexor (%, mean±SD)	
$FATI_1$	22±8
$FATI_2$	10±7
$FATI_3$	22±8

One female subject was omitted from the fatigue index analysis. Her left flexor muscle measurement failed because of sudden pain in the muscles. The subject achieved the maximum torque of 38 Nm at 2.8 s, and the torque immediately dropped to 2 Nm and during the rest of the period the torque did not rise above 8 Nm.

Although the reliability coefficients were highest in $FATI_3$, there were no statistically significant differences in the repeatability between the three indices either in extension ($p=0.7071$) or flexion ($p=0.9684$). However, there were differences between the levels of muscle torque between the indices $FATI_1$, $FATI_2$ and $FATI_3$ ($p<0.0001$). $FATI_3$ gave the highest values (in fatigue indices). In extension, the limits of agreement were 0.62 (-2.51, 3.77) and 20.50 (17.35, 23.63) between $FATI_3$ and $FATI_2$, and –2.24 (-2.81, -1.66) and 1.39 (0.82, 1.97) between $FATI_3$ and $FATI_{1.}$ A significant positive correlation between the mean value and difference of $FATI_3$ and $FATI_1$ in extension was found ($r=0.51$, $p=0.0041$). In flexion, the limits of agreement were –2.00 (-2.48, -1.52) and 1.05 (0.57, 1.53) between $FATI_3$ and $FATI_1$, and 0.34 (-3.29, 3.98) and 23.34 (19.70, 26.97) between $FATI_3$ and $FATI_2$.

A correlation was observed between the maximal isometric flexion torque and the fatigue index $FATI_1$ ($r=-0.45$, $p<0.05$) and, similarly, between the maximal isometric flexion torque and the fatigue index $FATI_3$ ($r=-0.46$, $p<0.05$), indicating that a low maximal torque is related with high fatigue resistance. There were no correlations between the maximal 5 s isometric torque and $FATI_{2.}$

Discussion

The test-retest reliability of the isometric maximal voluntary torque was very high, ICC values above 0.90 are considered to be very high [27]. This confirms the findings in previous studies that knee dynamometer is reliable in assessing maximal voluntary isometric force of knee muscles [9,26], and stationary knee muscle dynamometer is useful compared with hand-held dynamometer measurement, which in previous studies has shown lower reliability in testing large muscles [1,2]. The advantage of hand-held dynamometer is in its portability, but on the other hand the measurement is depended of the strength of the examiner, and consequently the individual variations of examiners may cause a lot of variability in measurements.

Measurement of static fatigue was highly reproducible in all three indices in this study. $FATI_3$ gave the highest inter-rater reliability coefficients (ICC) as compared with $FATI_1$ and $FATI_2$. Thus, it can be suggested that $FATI_3$ is a more accurate index than the two others. The indices $FATI_1$ and $FATI_2$ were also highly reliable in a study of Schwid *et al.* [22] while in their study the dynamic fatigue index showed poor reliability in repeated measures in healthy subjects (ICC=0.20). Similarly, in a study of Pincivero *et al.* (18) the reliability was low (ICC=0.26) in repeated measures for the dominant leg.

The intra-rater reliabilities (ICC) were highest in $FATI_1$ and $FATI_3$. In $FATI_2$ the time period from 0 to 5 s is totally omitted, while in $FATI_1$ the initial 5 s period is included in the fatigue index calculation. As visualised in Figs 3a and 3b, the Time Point of Maximum (TPM) value of the muscle torque is usually achieved by 2-3 s, and from that point onwards, the torque declines. Thus, the decline has probably continued for a couple of seconds before the fatigue index calculation begins at 5 s. These first five seconds may contain hidden information about the torque development. We also found a correlation between the maximal 5 s isometric flexion torque and $FATI_3$, suggesting that the subjects who exerted high maximal torque rapidly (during 5 s) had lower fatigue resistance. It is very difficult to find this causality by using the fatigue index $FATI_{2.}$

We had no opportunity to use any visual feedback during fatigue measurements, but if the force signal had been displayed on a monitor for the subjects, the subjects might have acted differently then. Especially at the beginning of the force production, which was essential for fatigue index calculation, and even at the end they might have been able to produce more force with on-line visual feedback. There is evidence [11] indicating that maximal voluntary force is usually less than the true maximal force. Therefore, we measured maximal voluntary force, with a possible force reserve being unutilized in the muscles. The lower maximal torque was related to the higher fatigue resistance in this study, and possible explanations to that might be that greater absolute forces are associated with increased intramuscular pressure, occlusion of blood flow, metabolic accumulation, increased metaboreflex response and decreased oxygen delivery to the muscles [4,15,21,23]. Further, several studies have shown that stronger subjects are less fatigue resistant [12,13,19].

During the measurement period of 30 s is mainly anaerobically driven, requiring major contribution of glycolytic metabolism [3,28]. The proportion of aerobic energy supply increases when the measurement period is longer than 30 s, after which the work is performed at a lower level. A measurement period of 45 s might be more appropriate for evaluating the fatigability of subjects with varying physiological capacities; ranging from sedentary subjects to endurance and power athletes. Another limitation in the present study was the small number of participants. With larger number of men and women we would have reached better statistical power.

To conclude, knee muscle strength and fatigability can objectively be measured by using a fixed dynamometer. The reliability of maximal voluntary isometric strength was high and all three fatigue indices, based on the calculation of Area Under Force vs. time Curve, were found reliable in assessing the test-retest fatigability of knee extensors and flexors during a sustained 30 s muscle contraction. However, we suggest that the fatigue index $FATI_3$, with the actual time point of maximal torque as the starting point for calculation, is the most accurate index. Additional studies are still necessary for developing accurate and sensitive methods feasible in measuring fatigability in healthy subjects.

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