The Knee 20 (2013) 250–255

Contents lists available at SciVerse ScienceDirect

The Knee

# Robotic knee laxity testing: Reliability and normative data

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ARTICLE INFO

*Article history:*
Received 22 May 2012
Received in revised form 13 October 2012
Accepted 20 October 2012

*Keywords:*
Anterior cruciate ligament
Electromyography
Force
Arthrometry

ABSTRACT

*Purpose:* To evaluate the reliability of the GeNouRoB knee arthrometer and present normative values of knee anterior laxity using this device on young females.
*Methods:* Anterior laxity in both knees was tested in two groups of young, uninjured females using the hamstrings electromyography biofeedback feature of the device. There were 13 participants in the group tested for reliability and 23 for the normative study. Laxity (mm of movement of the proximal tibia in the anterior direction relative to the femur) was calculated at test forces of 134 N and 250 N with values presented for the unstandardised and standardised (relative to stabilisation force) conditions.
*Results:* The relative reliability (95% limits of agreement) of the device for laxity at a test force of 134 N was 2 to 3 mm. Left knee anterior laxity was almost 1 mm greater than the right.
*Conclusions:* The relative reliability of the GeNouRoB arthrometer is comparable to the KT device. In agreement with previous work on the nonrobotic KT arthrometer, the knee anterior laxity values found with the GeNouRoB are greater in the left as compared to the right knee.


## 1. Introduction

Anterior laxity is a risk factor for anterior cruciate ligament [1] and traumatic knee injuries [2], generally, in the uninjured knee. In the injured knee, it is indicative of anterior cruciate ligament injury [3,4]. In the injured knee some studies have shown that the amount of anterior laxity is related to physical function [5,6]. These papers highlight the importance of testing knee joint anterior laxity.

Optimal joint laxity testing requires that an appropriate and known force be applied to the joint segment being moved. Additionally, this load should be applied at a consistent speed [7] and perpendicular to the moved segment. Other requirements to optimal testing, and retesting, include methods to ensure full relaxation of the muscles [8–10] that surround the tested joint and consistent application of force to the joint segment being stabilised during the testing. For knee anterior laxity instrumented testing, the most popular device used in the research literature is the KT knee ligament arthrometer. This device fulfils the first requirement of optimal testing (applying known loads to the distal segment) but its abilities in the other requisites of optimal testing are questionable, if not absent.

A new knee ligament arthrometer for testing anterior laxity, the GenouRoB (GeNouRoB SAS, Montenay, France), has been developed and is now available commercially. This robotic device attempts to offer additional characteristics that may improve testing as compared to nonrobotic devices such as the KT. In particular, its robotic nature heightens the possibility that known loads will be applied at a consistent speed and direction to the lower leg while the proximal segment is stabilised at known forces with this occurring consistently. Additionally, this test system includes electromyography (EMG) as a method to ensure relaxation of the surrounding musculature. This is considered crucial as even small degrees of contraction of one key group, the hamstrings, can significantly affect results [11].

The developers of the GeNouRoB have presented results of reliability testing [12]. Only one independent study of the GeNouRoB has been published and it concluded that the intra- and inter-rater reliability of this device is superior to the KT but the results were not clearly presented [13]. Furthermore, normative data for the GeNouRoB has not been presented. The purpose of this work, therefore, was to evaluate the intra-rater reliability of this device (Study 1) and to present normative data for one group of females (Study 2).

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0968-0160/$ – see front matter 
http://dx.doi.org/10.1016/j.knee.2012.10.010

## 2. Methods

### 2.1. Study 1

Subjects were 15 female physical therapists or university students in Ljubljana, Slovenia. None of them had a history of arthrometric knee laxity testing. They attended two test sessions on one day with at least a 1 hour interval between sessions. Prior to knee laxity testing, their age, body mass and height, and leg dominance (leg used to kick a ball) were recorded. Additionally, participants were asked about whether they were active in recreational sports and, if so, how often they participated each week. Whether they were using hormonal contraception and whether they were having a regular menstrual cycle was also recorded.

Laxity was tested using the GeNouRoB knee arthrometer. All measurements of knee joint sagittal laxity were performed by the most experienced knee arthrometric examiner in Slovenia (primary author). The leg to be tested first was determined randomly.

Two active EMG electrodes were placed on the hamstrings of the test leg approximately 1/3 the distance from the line of the gluteal fold to the insertions of the muscle group. An inactive electrode was placed on the lateral side of the test knee. Subjects were positioned and the GeNouRoB was applied according to the manufacturer's instructions as displayed in Fig. 1. Subjects lay supine on an examination table with their body in line with the GeNouRoB. The knee joint line was positioned directly above the junction between the thigh support and the calf support. The lower edge of the GeNouRoB patella shell was aligned with the apex of the patella. The patella and foot of the test leg were then secured with the shells and securing straps of the GeNouRoB. The GeNouRoB displacement sensor was then positioned on the tibial tuberosity at an angle of 90°. It was then ensured that the subject found the positioning comfortable and that there would not be excessive rotation of the test leg. The position of the heel on the GeNouRoB was recorded using the scale provided on the heel support platform and this value was used in retesting. Prior to test initiation, the upper part of the displacement sensor rod was positioned between 0.5 cm and 2.5 cm and the GeNouRoB system checks that the sensor is correctly positioned.

To optimise the EMG signal, the following methods were performed by the examiner who wore rubber soled shoes. After the subject was positioned and stabilised the examiner made sure that the subject was not touching any metal, that no cell phones were in the test area and that the subject was not touched during the testing. The participant was then asked to completely relax their test leg. Once the examiner was convinced of participant relaxation and external noise had been brought to a minimum the GeNouRoB computer screen was evaluated. If there was a green bar on the EMG signal image, the sensitivity dial on the GeNouRoB was slowly turned clockwise by the examiner until the green bar just disappeared from the screen. Excessive turning of the sensitivity dial clockwise more than necessary was avoided to ensure that the system was not disabled from detecting important, low levels of muscular contraction. In cases where there was no green bar on the EMG signal, the sensitivity dial was turned counterclockwise until the green bar appeared on the screen, then turned clockwise until the green bar just disappeared from the screen.

**Fig. 1.** View of GNRB arthrometer on the left knee of an individual with extra strapping placed across the distal thigh on the test leg just proximal to the device's patellar stabilisation.

The GeNouRoB device was then activated to perform the following tests: 1) six repetitions at 134 N without additional strapping, 2) six repetitions at 250 N without additional strapping, 3) six repetitions at 134 N with additional strapping (see below), and 4) six repetitions at 250 N with additional strapping. After this the individual was removed from the device and the device was then applied to the second leg and testing repeated as above. Additional strapping consisted of placing an inflexible strap around the leg and table just proximal to the test leg's superior border of the patella (Fig. 1). The strap was tightened to the greatest level tolerated by the participant.

The mean of the first three repetitions for each session (1 and 2) and condition (test force, strap, leg) was calculated for each participant and used in the statistical analysis. Statistical analysis planning was guided by the work of Atkinson and Nevill [14] and consisted of calculation of the ICC (2,1) to evaluate relative reliability. To evaluate absolute reliability the standard errors of measurement were calculated. The variance of measurements was visually inspected using Bland and Altman plots and 95% limits of agreement. The Bland and Altman 95% limits of agreement were calculated for each condition (leg, test force, strap vs unstrapped) using this formula: mean of (session 1 mean laxity − session 2 mean laxity) ± 1.96 (standard deviation of (session 1 mean laxity − session 2 mean laxity)).

### 2.2. Study 2

Subjects were 23 females working at the Zrece Thermal Spa in Slovenia. All of the subjects had been tested previously on the GeNouRoB at least 3 months prior. They attended one test session. Prior to knee laxity testing, their age, body mass and height, and leg dominance (leg used to kick a ball) were recorded. Additionally, participants were asked about whether they were active in recreational sports and, if so, how often they participated each week plus the number of hours of participation. Additionally, each participant completed the Tegner activity scale in order to estimate the intensity of their physical activities relative to the knee.

Testing was similar to that used in Study 1 except no strapping was used in the GeNouRoB testing and only four repetitions per leg were taken, all at 250 N. From these four repetitions the laxity at 134 N and 250 N was noted.

The purpose of the data analysis was performed in such a way as to make results useful for clinicians and researchers and comparable to the two key papers in this area: Robert et al. [12], the only study in the literature where results are presented for the GeNouRoB, and Vauhnik et al. [15], where the examiner was the same as in the present work and the sample was similar in age, gender, etc. To attempt to match the type of analysis of the former study the following were calculated: 1) averages of all trials for each test load and leg, 2) averages of all trials after deleting the first repetition, and 3) presenting differences between legs for each trial repetition as well as differences between legs after the averaging in 1) and 2) were completed. These results were calculated for absolute and signed values. To make it possible to compare the results to the work of Vauhnik et al. [15] the left and right leg laxity values were combined and averaged. Finally, once the results of Study 1 were known showing some indications that reliability increases when the laxity values are divided by the patellar stabilisation force, we added calculations of laxity/patellar stabilisation force to the analysis for Study 2.

## 3. Results

### 3.1. Study 1

Of the 15 subjects, the data for two were not included in the analysis because their testing could not be completed due to knee pain during testing. In particular, one of these subjects reported pain during testing regardless of the strapping condition while the other only had pain during testing with the strapping. For the 13 subjects who completed the testing and were included in the analysis, their characteristics are presented in Table 1. All the participants were right leg dominant and the right leg was tested first in six of the subjects. Five of the group used hormonal pregnancy prophylaxis and one of the subjects was postmenopausal, with all except two of the remaining participants reporting normal menstruation. Finally, all except one of the 13 subjects was active in recreational sport with the frequency of participation reported in Table 1. Table 2 contains additional information about the test characteristics and the laxity/patellar stabilisation force results.

#### 3.1.1. Relative reliability

The ICCs (2,1) for the relationship between the mean of the first three repetitions of the first session to the first three repetitions of the second session for each condition (force, strap and leg) are found in Table 3. In addition to this measurement of relative reliability, this Table contains two measures of absolute reliability, the standard error of measurement and the 95% limits of agreement.

When considering the two way ANOVA used in ICC calculations, we assume that the observed differences within a subject come from two sources: measurement error and the variability introduced by testing in different sessions. With only two sessions whose measurements are on average 0.5 apart, this part of variance is approximately equal to 0.25 and thus not an important part of the whole. Therefore, the lack of reliability can be almost entirely attributed to measurement error.

As noted in Table 3, the ICC values for laxity tend to be higher with the 134 N test force, they are always higher on the left leg, but no trend is seen for strapping. The largest differences seem to be due to the leg tested. When comparing the two forces, both the between subject variance and the within patient variance are higher for the higher force. This means that the individual averages vary more when the higher force is applied, but also that the measurements on the same subject vary more when the higher force is applied. When comparing the two legs, the results are almost inverse. The within subject variance is almost always smaller for the left leg, implying that the measurement error is smaller for the left leg, while the between target variance is always larger on the left leg. These latter differences are particularly large, the individual averages on the left leg differ considerably more than the individual averages on the right leg.

When laxity was standardised relative to the patellar stabilisation force used in testing, the patterns are similar to unstandardised laxity in that the ICC values tend to be higher with the 134 N as compared to the 250 N test force and no trend is seen for strapping. The pattern is different from laxity alone where ICC values are higher on the left leg for the 134 N test and right leg for the 250 N test. Finally, when comparing the ICC values for the laxity alone vs. laxity standardised to the patellar stabilisation force, differences are notable between the left and right knees for both test forces (134 and 250 N). In the 134 N test the ICCs are similar between standardised and unstandardised laxity for the left leg while for the right knee standardisation increases the ICC. In the 250 N testing the ICCs differ in the standardised vs. unstandardised laxity conditions for both knees and differ between knees in that the left knee ICCs are greater in the latter condition (i.e. higher in the unstandardised) and the opposite holds true for the right knee (as also found in the 134 N test).

#### 3.1.2. Absolute reliability

As for absolute reliability, besides the standard error of measurement (Table 3), Bland–Altman plots were visually reviewed for each individual and each combination of force, strap and leg and an example of one of these is presented in Fig. 2. The measurement in the first and second sessions is compared with mean values given on the X-axis, while the difference between the sessions is given on the Y-axis. As noted in these Figures, there is practically no heteroscedasticity and the variance does not depend importantly on either strap or force. That is, measurement error is similar between the strapped and unstrapped conditions and between the 134 N and 250 N tests. Finally, Table 3 contains the 95% limits of agreement for each condition.

### 3.2. Study 2

The characteristics of the participants in this portion of the project are presented in Table 4. All but two of the 23 subjects were active in recreational sport with the weekly frequency and duration of participation reported in Table 4. As for Tegner scores of physical activity intensity relative to the knee (0–10 scale), the frequencies of scores were as follows: three participants scored 3, seven scored 4, three scored 5, nine scored 6, and one scored 7, the highest score reported.

## 4. Discussion

The relative reliability (95% limits of agreement) of the GNRB device for laxity at a test force of 134 N was 2 to 3 mm. Knee anterior laxity when tested in the unstrapped condition differed slightly from one test session to the next with left knee laxity at 134 N averaging 6.2 and 6.5 mm in sessions 1 and 2, respectively, and 9.8 and 10.5 mm at 250 N in sessions 1 and 2, respectively. In the right knee at 134 N laxity averaged 5.6 and 5.9 mm in sessions 1 and 2, respectively. At 250 N, laxity averaged 9.2 and 9.5 mm in sessions 1 and 2, respectively.

### 4.1. Study 1

The most important property of the ICC is that its value depends on both the measurement error and the between target variability. This makes it a good measure of actual performance of the device being tested, but does not allow direct comparisons between tools used in different studies. For this reason, we also reported absolute

**Table 1**
Characteristics of the participants and knee laxity results in the reliability portion of the study (N = 13).

| Variable | Mean | Standard deviation | Minimum | Maximum | |
|---|---|---|---|---|---|
| Age (years) | 29.4 | 9.5 | 18 | 51 | |
| Height (cm) | 166 | 6 | 160 | 179 | |
| Mass (kg) | 62 | 6 | 52 | 74 | |
| Body mass index (kg/m$^2$) | 22.4 | 2.0 | 19.3 | 25.5 | |
| Sports frequency per week | 3.2 | 1.4 | 0 | 5 | |
| *Knee anterior laxity (mm)* | | | | | *Coefficient of variation* |
| Unstrapped 134 N test force, 1st 3 repetitions average, session 1, left | 6.2 | 1.5 | 4.5 | 9.6 | 0.242 |
| Unstrapped 134 N test force, 1st 3 repetitions average, session 1, right | 5.6 | 1.2 | 3.1 | 7.4 | 0.214 |
| Unstrapped 134 N test force, 1st 3 repetitions average, session 2, left | 6.5 | 1.5 | 4.2 | 10.1 | 0.231 |
| Unstrapped 134 N test force, 1st 3 repetitions average, session 2, right | 5.9 | 1.7 | 3.2 | 9.7 | 0.288 |
| Strapped 134 N test force, 1st 3 repetitions average, session 1, left | 5.7 | 1.6 | 3.8 | 9.2 | 0.281 |
| Strapped 134 N test force, 1st 3 repetitions average, session 1, right | 4.9 | 1.1 | 3.3 | 7.5 | 0.224 |
| Strapped 134 N test force, 1st 3 repetitions average, session 2, left | 6.3 | 1.6 | 4.9 | 10.1 | 0.254 |
| Strapped 134 N test force, 1st 3 repetitions average, session 2, right | 5.4 | 1.5 | 3.0 | 8.1 | 0.278 |
| Unstrapped 250 N test force, 1st 3 repetitions average, session 1, left | 9.8 | 1.7 | 7.2 | 13.3 | 0.173 |
| Unstrapped 250 N test force, 1st 3 repetitions average, session 1, right | 9.2 | 1.4 | 6.0 | 11.1 | 0.152 |
| Unstrapped 250 N test force, 1st 3 repetitions average, session 2, left | 10.5 | 1.9 | 8.2 | 14.5 | 0.181 |
| Unstrapped 250 N test force, 1st 3 repetitions average, session 2, right | 9.5 | 1.9 | 6.5 | 13.4 | 0.200 |
| Strapped 250 N test force, 1st 3 repetitions average, session 1, left | 9.0 | 1.9 | 6.1 | 13.2 | 0.211 |
| Strapped 250 N test force, 1st 3 repetitions average, session 1, right | 8.3 | 1.3 | 6.1 | 10.8 | 0.157 |
| Strapped 250 N test force, 1st 3 repetitions average, session 2, left | 10.0 | 1.6 | 8.2 | 13.6 | 0.160 |
| Strapped 250 N test force, 1st 3 repetitions average, session 2, right | 8.6 | 1.7 | 5.9 | 11.5 | 0.198 |

**Table 2**
GNRB knee anterior laxity test patellar stabilisation forces and laxity (mm)/patellar stabilisation force values in the reliability portion of the study (N = 13).

| Variable | Mean | Standard deviation | Minimum | Maximum | Coefficient of variation |
|---|---|---|---|---|---|
| *Patellar stabilisation force (N)* | | | | | |
| Unstrapped 134 N test force, 1st 3 repetitions average, session 1, left | 50 | 5 | 42 | 63 | 0.100 |
| Unstrapped 134 N test force, 1st 3 repetitions average, session 1, right | 49 | 3 | 44 | 56 | 0.061 |
| Unstrapped 134 N test force, 1st 3 repetitions average, session 2, left | 51 | 5 | 44 | 65 | 0.098 |
| Unstrapped 134 N test force, 1st 3 repetitions average, session 2, right | 49 | 3 | 45 | 55 | 0.061 |
| Strapped 134 N test force, 1st 3 repetitions average, session 1, left | 60 | 5 | 55 | 72 | 0.083 |
| Strapped 134 N test force, 1st 3 repetitions average, session 1, right | 61 | 5 | 53 | 70 | 0.082 |
| Strapped 134 N test force, 1st 3 repetitions average, session 2, left | 63 | 6 | 55 | 77 | 0.095 |
| Strapped 134 N test force, 1st 3 repetitions average, session 2, right | 62 | 4 | 54 | 68 | 0.065 |
| Unstrapped 250 N test force, 1st 3 repetitions average, session 1, left | 47 | 5 | 42 | 56 | 0.106 |
| Unstrapped 250 N test force, 1st 3 repetitions average, session 1, right | 46 | 4 | 37 | 53 | 0.087 |
| Unstrapped 250 N test force, 1st 3 repetitions average, session 2, left | 47 | 6 | 37 | 60 | 0.128 |
| Unstrapped 250 N test force, 1st 3 repetitions average, session 2, right | 46 | 3 | 41 | 53 | 0.065 |
| Strapped 250 N test force, 1st 3 repetitions average, session 1, left | 58 | 5 | 51 | 70 | 0.086 |
| Strapped 250 N test force, 1st 3 repetitions average, session 1, right | 58 | 5 | 50 | 67 | 0.086 |
| Strapped 250 N test force, 1st 3 repetitions average, session 2, left | 59 | 6 | 51 | 76 | 0.102 |
| Strapped 250 N test force, 1st 3 repetitions average, session 2, right | 59 | 3 | 53 | 64 | 0.051 |
| *Anterior laxity (mm)/patellar stabilisation force (N)* | | | | | |
| Unstrapped 134 N test force, 1st 3 repetitions average, session 1, left | 0.129 | 0.043 | 0.078 | 0.218 | 0.333 |
| Unstrapped 134 N test force, 1st 3 repetitions average, session 1, right | 0.114 | 0.027 | 0.061 | 0.155 | 0.237 |
| Unstrapped 134 N test force, 1st 3 repetitions average, session 2, left | 0.129 | 0.034 | 0.083 | 0.201 | 0.264 |
| Unstrapped 134 N test force, 1st 3 repetitions average, session 2, right | 0.121 | 0.038 | 0.066 | 0.196 | 0.314 |
| Strapped 134 N test force, 1st 3 repetitions average, session 1, left | 0.096 | 0.031 | 0.058 | 0.156 | 0.323 |
| Strapped 134 N test force, 1st 3 repetitions average, session 1, right | 0.081 | 0.022 | 0.052 | 0.141 | 0.272 |
| Strapped 134 N test force, 1st 3 repetitions average, session 2, left | 0.101 | 0.024 | 0.078 | 0.159 | 0.238 |
| Strapped 134 N test force, 1st 3 repetitions average, session 2, right | 0.087 | 0.026 | 0.047 | 0.132 | 0.299 |
| Unstrapped 250 N test force, 1st 3 repetitions average, session 1, left | 0.213 | 0.053 | 0.130 | 0.298 | 0.249 |
| Unstrapped 250 N test force, 1st 3 repetitions average, session 1, right | 0.204 | 0.039 | 0.136 | 0.263 | 0.191 |
| Unstrapped 250 N test force, 1st 3 repetitions average, session 2, left | 0.228 | 0.058 | 0.162 | 0.370 | 0.254 |
| Unstrapped 250 N test force, 1st 3 repetitions average, session 2, right | 0.206 | 0.048 | 0.140 | 0.293 | 0.233 |
| Strapped 250 N test force, 1st 3 repetitions average, session 1, left | 0.158 | 0.040 | 0.099 | 0.236 | 0.253 |
| Strapped 250 N test force, 1st 3 repetitions average, session 1, right | 0.144 | 0.030 | 0.106 | 0.217 | 0.208 |
| Strapped 250 N test force, 1st 3 repetitions average, session 2, left | 0.170 | 0.027 | 0.137 | 0.226 | 0.159 |
| Strapped 250 N test force, 1st 3 repetitions average, session 2, right | 0.146 | 0.030 | 0.097 | 0.198 | 0.205 |

reliability. The 95% limits of agreement (LoA) for laxity in the unstrapped condition (134 and 250 N test forces) in the present study are 2 to 3 mm at the 134 N laxity test with test sessions for each participant occurring on the same day. Myrer et al. [16] reported LoA values of 1.65 mm and 1.94 mm for the right knee testing using the KT at 134 and 178 N, respectively, in 30 uninjured university students (13 females) with the second test occurring 2 days to 2 weeks after the first. Left knee results were not reported. Queale et al. [17]. reported LoA values of 2.0 mm for KT testing at 89 N in the ACL-injured knee of 10 individuals (3 females) on separate days. Although the values across these studies appear similar, the best comparison between devices remains to be reported in a study where the two devices are compared in testing of one sample. Perhaps the most important aspect of this discussion to the clinician is to know that knee anterior laxity changes of less than 2 mm or even 3 mm from one test session to the next in a single knee is likely to be due to measurement error and not due to changes in actual knee laxity.

In reviewing Table 3 for ICC differences between the right and left knees for unstandardised (relative to stabilisation force) laxity, the

**Table 3**
Intra-rater reliability of the GNRB for knee anterior laxity and knee anterior laxity divided by patellar stabilisation force (N) in one examiner (n = 13).

| Test force (N) | Strapped? | Leg | ICC (2,1) | Standard error of measurement | 95% limits of agreement (mm) |
|---|---|---|---|---|---|
| *Knee anterior laxity (mm)* | | | | | |
| 134 | No | Left | 0.786 | 0.5 | $-0.3 \pm 2.0$ |
| | No | Right | 0.467 | 1.1 | $-0.3 \pm 3.1$ |
| | Yes | Left | 0.736 | 0.7 | $-0.5 \pm 2.7$ |
| | Yes | Right | 0.450 | 0.8 | $-0.6 \pm 2.2$ |
| 250 | No | Left | 0.643 | 1.0 | $-1.0 \pm 3.2$ |
| | No | Right | 0.338 | 1.3 | $-0.3 \pm 3.1$ |
| | Yes | Left | 0.522 | 1.3 | $-0.2 \pm 3.9$ |
| | Yes | Right | 0.463 | 1.1 | $-0.7 \pm 3.0$ |
| *Knee anterior laxity divided by patellar stabilisation force (mm/N)* | | | | | |
| 134 | No | Left | 0.784 | 0.012 | $0.000 \pm 0.052$ |
| | No | Right | 0.604 | 0.018 | $-0.007 \pm 0.059$ |
| | Yes | Left | 0.730 | 0.011 | $-0.005 \pm 0.041$ |
| | Yes | Right | 0.598 | 0.014 | $-0.007 \pm 0.043$ |
| 250 | No | Left | 0.514 | 0.038 | $-0.015 \pm 0.110$ |
| | No | Right | 0.531 | 0.029 | $-0.002 \pm 0.086$ |
| | Yes | Left | 0.349 | 0.032 | $-0.012 \pm 0.078$ |
| | Yes | Right | 0.690 | 0.014 | $-0.002 \pm 0.049$ |

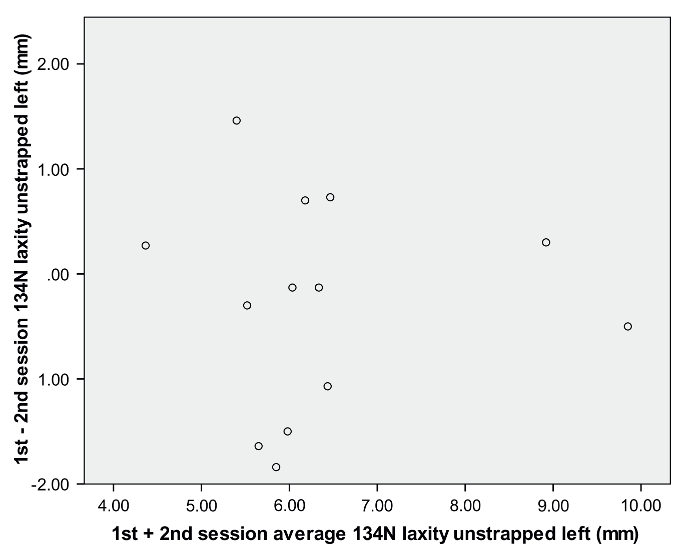


**Fig. 2.** Bland–Altman plot of average knee anterior laxity over sessions 1 and 2 (X-axis) relative to difference in laxity between sessions 1 and 2 for the 134 N test in the left knee when unstrapped.

**Table 4**
Characteristics of the participants in the normal portion of the study (n = 23).

| Variable | Mean | Standard deviation | Minimum | Maximum |
|---|---|---|---|---|
| Age (years) | 34 | 8 | 20 | 49 |
| Body mass (kg) | 68 | 12 | 54 | 89 |
| Body height (cm) | 167 | 4 | 160 | 174 |
| BMI (kg/m$^{sss}$) | 24.1 | 3.9 | 19.0 | 31.3 |
| Tegner ($/_{10}$) | 4.9 | 1.2 | 3 | 7 |
| Physical activity frequency (per week) | 2.9 | 1.6 | 0 | 5.0 |
| Physical activity duration (hours per week) | 3.3 | 2.6 | 0 | 12.0 |
| R knee anterior laxity (134 N test) repetitions 1-3 average | 5.2 | 1.6 | 2.6 | 8.4 |
| R knee anterior laxity (134 N test) repetitions 2-4 average | 5.2 | 1.5 | 2.7 | 8.6 |
| R knee anterior laxity (134 N test) all 4 repetitions average | 5.2 | 1.5 | 2.6 | 8.5 |
| R knee anterior laxity (250 N test) repetitions 1-3 average | 8.6 | 2.0 | 5.5 | 12.6 |
| R knee anterior laxity (250 N test) repetitions 2-4 average | 8.5 | 1.9 | 5.6 | 12.7 |
| R knee anterior laxity (250 N test) all 4 repetitions average | 8.6 | 1.9 | 5.5 | 12.6 |
| L knee anterior laxity (134 N test) repetitions 1-3 average | 6.1 | 1.6 | 3.3 | 9.4 |
| L knee anterior laxity (134 N test) repetitions 2-4 average | 6.1 | 1.6 | 3.5 | 9.7 |
| L knee anterior laxity (134 N test) all 4 repetitions average | 6.1 | 1.6 | 3.4 | 9.5 |
| L knee anterior laxity (250 N test) repetitions 1-3 average | 9.5 | 1.8 | 6.7 | 13.1 |
| L knee anterior laxity (250 N test) repetitions 2-4 average | 9.4 | 1.8 | 6.7 | 13.3 |
| L knee anterior laxity (250 N test) all 4 repetitions average | 9.5 | 1.8 | 6.7 | 13.2 |
| Combined L and R knee anterior laxity (134 N test) repetitions 1-3 average | 5.6 | 1.5 | 3.2 | 8.9 |
| L–R knee anterior laxity (134 N test) all 4 repetitions average | 0.9 | 1.0 | −1.6 | 3.6 |
| L–R knee anterior laxity (134 N test) repetitions 2-4 average | 0.9 | 1.0 | −1.2 | 3.6 |
| L–R knee anterior laxity (134 N test) repetition 1 | 0.9 | 1.5 | −2.8 | 3.7 |
| L–R knee anterior laxity (134 N test) repetition 2 | 0.8 | 1.0 | −1.3 | 3.6 |
| L–R knee anterior laxity (134 N test) repetition 3 | 0.9 | 1.0 | −1.2 | 3.6 |
| L–R knee anterior laxity (134 N test) repetition 4 | 1.0 | 1.0 | −1.1 | 3.6 |
| Abs L–R knee anterior laxity (134 N test) all 4 repetitions average | 1.1 | 0.8 | 0.0 | 3.6 |
| Abs L–R knee anterior laxity (134 N test) repetitions 2-4 average | 1.1 | 0.8 | 0.1 | 3.6 |
| Abs L–R knee anterior laxity (134 N test) repetition 1 | 1.4 | 1.0 | 0.1 | 3.7 |
| Abs L–R knee anterior laxity (134 N test) repetition 2 | 1.1 | 0.8 | 0.1 | 3.6 |
| Abs L–R knee anterior laxity (134 N test) repetition 3 | 1.1 | 0.8 | 0.0 | 3.6 |
| Abs L–R knee anterior laxity (134 N test) repetition 4 | 1.1 | 0.7 | 0.3 | 3.5 |
| PS force (N) in right knee laxity test, repetition 1 | 51 | 3 | 46 | 58 |
| PS force (N) in right knee laxity test, repetition 2 | 48 | 4 | 39 | 57 |
| PS force (N) in right knee laxity test, repetition 3 | 47 | 4 | 38 | 56 |
| PS force (N) in right knee laxity test, repetition 4 | 46 | 4 | 37 | 54 |
| PS force (N) in right knee laxity test, repetitions 1-3 average | 49 | 4 | 43 | 57 |
| PS force (N) in right knee laxity test, repetitions 2-4 average | 47 | 4 | 38 | 55 |
| PS force (N) in right knee laxity test, all repetitions average | 48 | 4 | 41 | 56 |
| PS force(N)in left knee laxity test, repetition 1 | 56 | 8 | 47 | 84 |
| PS force (N) in left knee laxity test, repetition 2 | 52 | 9 | 40 | 73 |
| PS force (N) in left knee laxity test, repetition 3 | 49 | 8 | 36 | 71 |
| PS force (N) in left knee laxity test, repetition 4 | 48 | 8 | 34 | 69 |
| PS force (N) in left knee laxity test, repetitions 1-3 average | 52 | 8 | 42 | 76 |
| PS force (N) in left knee laxity test, repetitions 2-4 average | 50 | 8 | 37 | 71 |
| PS force (N) in left knee laxity test, all repetitions average | 51 | 8 | 40 | 74 |
| Right knee laxity/PS force repetitions 2-4 average 134 N test (mm/N) | 0.112 | 0.035 | 0.058 | 0.190 |
| Left knee laxity/PS force repetitions 2-4 average 134 N test (mm/N) | 0.127 | 0.043 | 0.071 | 0.236 |
| Right knee laxity/PS force repetitions 2-4 average 250 N test (mm/N) | 0.181 | 0.046 | 0.111 | 0.280 |
| Left knee laxity/PS force repetitions 2-4 average 250 N test (mm/N) | 0.194 | 0.054 | 0.114 | 0.324 |

Abs = absolute value.
L = left, R = right.
PS = patellar stabilisation.

values are consistently less in the right knee. We know of no other study where differences in knee anterior laxity testing reliability between left and right knees have been investigated. Given the relatively small size of the sample, it is possible that this difference in reliability is not real. But if it is real, we can think of no obvious explanation. One possible explanation for manual, nonrobotic tests such as clinical laxity testing is examiner hand dominance [18] but this doesn't apply in this study given the robotic nature of the GeNouRoB testing. Another possible explanation concerns test order but six subjects were tested on the right leg first.

We anticipated that reliability would be greater when the patellar stabilisation force was accounted for in the analysis. This was found to be true for the right knee but the opposite was found for the left. We can think of no obvious explanation for this. In giving consideration to this, it is important to theorise about what might change the laxity found from one test session to the next. For a robotic device such as the GeNouRoB, we suspect that changes in its performance in terms of directions, amounts and speeds of force application would be minimal at most. Instead, we suspect that changes in the laxity noted from one session to the next, especially when both sessions occur on the same day as in the present study, are likely to be due to changes in joint position and the position of the device relative to the knee from session to session. With reference to the former, it is known that changes in tibial rotation will change the amount of anterior tibial displacement measured [19]. But we suspect that joint position changes are probably not as important in affecting laxity as are changes in the position of the device relative to the knee. If so, this highlights the importance of examiner performance in positioning subjects even with robotic laxity testing devices.

### 4.2. Study 2

The main points to be discussed are how knee laxity values found with the GeNouRoB in the present study compare to: 1) GeNouRoB values reported elsewhere, and 2) values found for the most commonly used device, the KT1000/2000. With reference to the former, only one study exists in the literature where the GeNouRoB was used [12]. Robert et al. [12] did not present normal values in their report thus making the present study the first to do this. The only data in their work with uninjured individuals that can be compared to the present study is their results concerning differences between the right and left knees where they noted "Mean differential displacement between right and left knees, at 134 N was 0.8 mm (IC at 95%: 0.7–0.94 mm) for the GNRB®." They further state that "308 pairs of measurements were recorded in 17 males and three females" who were engineering students aged from 19 to 22. We found it difficult to understand how many repetitions were performed in their two examiner study and to determine what was done with the collected data in terms of deleting and averaging values from repetitions, whether absolute values were used, etc. With these difficulties in mind we presented data in a number of ways that included 1) averaging all trials for each test load and leg, 2) averaging all trials after deleting the first repetition, and 3) presenting differences between legs for each trial repetition as well as differences between legs after the averaging in 1) and 2) were completed. These results were presented for absolute and signed values. Of these results, presented in Table 4, those for the non-absolute values appear to be the most comparable to the work of Robert et al. [12] in that the means all fall within their 95% confidence interval. These results show that the left knee anterior laxity is almost 1 mm greater than the right, when tested with the GeNouRoB device. In Vauhnik's PhD work with 616 females, the basis for one of the references in this study [15], the mean (SD, range) laxity on the right was 6.3 mm (1.5, 3–12) and 6.9 mm (1.4, 2–11) for the left. These results indicate either greater anterior laxity in the left knee or a false positive due to something about the examination or examiner. With reference to the latter, it is possible that the positioning of the subjects' legs is systematically different on the left as compared to right. As for the nature of the examination, test order may have had an effect in the present study as the right leg was tested first in all subjects. It is possible that this may have led to more participant hesitation in the leg tested first (right) with concomitant activation of the muscles around the joint resulting in less laxity being detected, even though the device is designed to limit hamstring muscle activity.

Given the common use of the KT arthrometers, it is important to consider the results of the present study relative to the anterior tibial translation values found using the KT. Of the many papers where normal values exist, the previous work of our team [15] seems most relevant given the fact that the present and previous work had the same examiner (RV) and evaluated similar populations. In the previous work, 616 Slovenian athletes aged between 11 and 41 (mean = 18 +/− 3.6) were assessed using a test load of 134 N in three repetitions with the average of the three repetitions calculated and presentation consisting of average laxity values for the combination of both legs. Average (+/− SD) knee laxity was 6.1 (1.3) mm with a range of 2.6 to 11.5 mm. Additional averages of the characteristics in the group included body height of 172 (7) cm, body mass of 63 (8) kg and body mass index of 18.3 (2.0) kg/m$^2$. These values can be compared to 167 (4) cm, 68 (12) cm and 24.1 (3.9), respectively, in the present study where the average laxity in the first three repetitions was 5.6 (1.5) mm with a range of 3.2 to 8.9 mm (Table 4). The average age in the present study was 34 (8) with a range of 20 to 49. Subjects in the present study were clearly older with a greater body mass index but neither of these factors appears to be related to knee anterior laxity in this age range [15]. What has been found to be related, negatively, to knee anterior laxity is body height as noted in univariate but not multivariate analysis (when sport type is accounted for) [15] but the taller group in the present study was the group with the greater laxity.

If the difference between studies in knee anterior laxity is due to the devices used in testing, then these results are surprising and require confirmation in a study where both devices are used on the same individuals. These results are surprising in that one would expect greater laxity in the group where attempts were made to eliminate the effects of hamstrings contraction on laxity, as was performed in the current study.

## Conflict of interest

No conflicts of interest exist for any of the authors of this paper.

## Acknowledgements

The authors would like to thank students from the University of Ljubljana and physiotherapists from the University Medical Centre Ljubljana, Department of Orthopaedic Surgery for participation in Study 1. For co-operation in Study 2, the authors would like to thank participants and physiotherapists Simona Pavlič Založnik, Katarina Skaza, Monika Škafar and Maša Lipovec Voglar at Terme Zreče Unitur Spa Resort in Slovenia. The participation of the corresponding author in the research project was funded by two resarch grants from the Slovenian Research Agency (J3 – 0178 – 0381 and TURAZ 78/0382 5100-17/2011-31).

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