

## A non-invasive device to objectively measure tibial rotation: verification of the device

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**Abstract** The purpose of this study was the correlation of the results of a new measurement device for tibial rotation (Rotameter) in comparison with the measurements of a knee navigation system as standard method. In a biomechanical laboratory study, all soft tissues were removed from 20 human cadaveric knees leaving only the intact capsule and the bone. Specific tracers were bicortically fixed in the bone in order to measure tibial rotation using a knee navigation system. The knees were fixed to a custom-made inside-boot to rule out undesirable rotation of the reconstruction inside the Rotameter measurement device.

Internal and external rotation values were measured at an applied torque of 5, 10 and 15 Nm. The different methods to evaluate tibial rotation were compared using the Pearson correlation coefficient. The correlations were deemed to be reliable if a value of  $\geq 0.80$  was achieved. At 5 Nm of applied torque, high correlations for the internal rotation, external rotation and the entire rotational range were found in the Pearson correlation coefficient between the Rotameter testing device in comparison with the knee navigation system as invasive reference method. These results were also confirmed at an applied torque of 10 and 15 Nm. In conclusion, the Rotameter testing device showed high correlations compared with the knee navigation system as an invasive standard method. It might be used as a non-invasive and easy alternative to investigate tibial rotation.

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### Introduction

The restoration of rotational stability is an important goal in the anatomical ACL reconstruction. However, the literature reports that single-bundle ACL reconstruction is insufficient in controlling combined rotational loads [23]. Thus, double-bundle ACL reconstruction might improve the rotational stability [8, 14, 24].

Manual measurements like the pivot shift or the dial test are mostly determined to measure the rotational stability. These tests are mostly not performed in a blind manner, which might influence the results, and tests like the pivot shift are therefore highly dependent on the experience and skills of examiners [16]. There is a lack of practical clinical

tools to objectively assess knee rotational laxities. Therefore, a device to measure tibial rotation would be of great value to further investigate rotational stability. As a result, greater knowledge of knee pathomechanics may facilitate improvements in surgical techniques, prosthetic design, injury prevention and joint degeneration [2]. The Rotameter as a new device to measure tibial rotation was developed, could show a high inter- and intra-observer reliability and was also able to reliably compare both sides in healthy participants [11].

A 3D digitization was able to investigate knee position adequately combined with MRI CT and radiostereometric analysis (RSA) [13]. As the navigation was previously used to assist ACL reconstruction and allowed for the 3D measurements of knee kinematics [3], the results of the Rotameter testing device were compared to the results of a knee navigation system which was used as an invasive standard method.

The purpose of this study was to verify a new objective measurement device for the tibial rotation.

## Materials and methods

Twenty fresh frozen human cadaver knees were used in a standard setting for the testing. A bone density scan was performed with all cadaver knees before testing in order to rule out incongruity of the bone density. All specimens were thawed at room temperature on the day of testing and all soft tissues were removed except for the intact capsule.

Pins with an infrared optical motion tracker were bicortically inserted in the tibial and the femoral bone. These trackers were oriented to be visualized by a knee navigation system (PrecisionN knee navigation system, Stryker Medical Systems, Duisburg, Germany) with special knee navigation software (Precision Knee Software, Stryker Medical Systems, Duisburg, Germany).

The Stryker PrecisionN knee (Fig. 1) navigation system which was developed to increase the efficiency of the total knee surgery is able to show the kinematics of the knee using an infrared three-camera system and infrared trackers. The 3D position of the knee can be appointed with an accuracy of 0.07 mm, respectively,  $0.07^\circ$ . An infrared pointer (Ortho Grip Knie-Pointer) is used to activate the system.

Through a 2 cm lateral incision, the acquired calibrating points inside the knee joint were digitized using the infrared pointer and scanned by the navigation system. A 3D model of the knee was calculated by the system which announces specific movements (flexion, extension, internal and external rotation) in real time mode. The incision was closed with a continuous suture.



**Fig. 1** The PrecisionN knee navigation system (Stryker Medical Systems, Duisburg, Germany) can measure the 3D kinematics of the knee using an infrared three-camera system (A) which can appoint the infrared trackers at the tibial and femoral bone. The measured rotation is shown on the navigation system screen

The femoral bone was fixed to the ground using  $90^\circ$  angulated screws which were bicortically inserted. The tibial bone was also fixed with screws to a metal bar which was cemented in a custom-made inside-boot. This inside-boot was used to rule out movement inside the Rotameter boot (Fig. 2a, b).

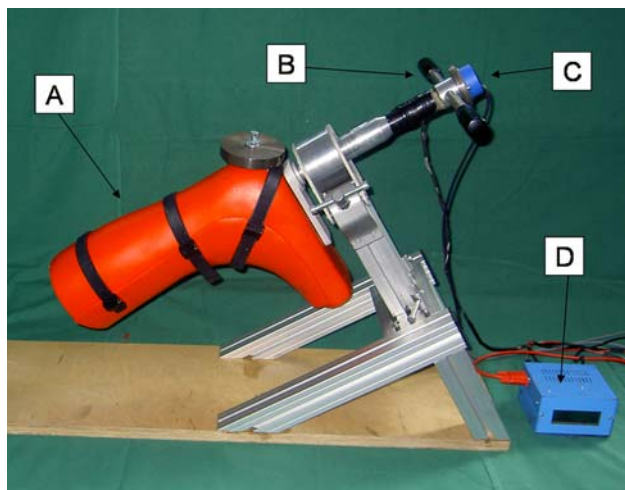
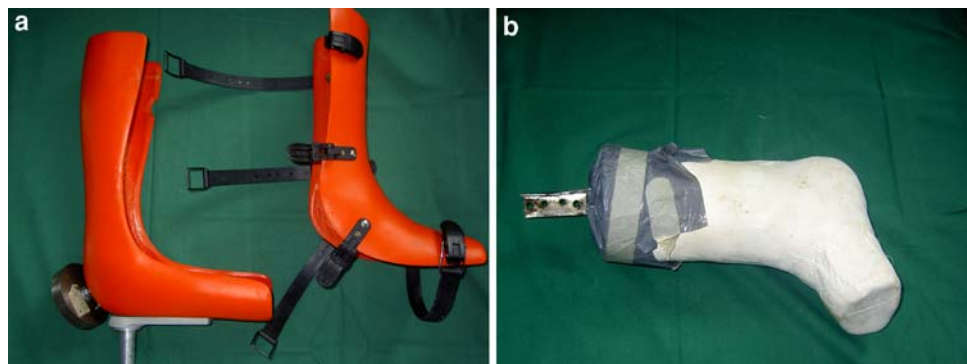
The Rotameter device was developed to measure isolated tibial rotation. The patient's position is leaned on the dial test (Fig. 3).

At the sole of the Rotameter boot, a handlebar is fixed which is able to apply different torques for the internal and external rotation. The measured rotational angles are transmitted to a computer system and are additionally shown digitally on the Rotameter device (Fig. 4).

The neutral position of the rotation was determined by the navigation system. At this point the Rotameter testing device was also set to  $0^\circ$ .

With the Rotameter a torque of 5, 10 and 15 Nm of external rotation was applied. The measurements were repeated three times in order to decrease the measurement error. The  $0^\circ$  point was checked again and 5, 10 and 15 Nm torque of internal rotation was applied in the same way. The measured values of the Rotameter testing device were compared to the measured values of the knee navigation system.

**Fig. 2** a/b: Inside the custom made Rotameter boot (a), a custom-made inside-boot with a cemented metal bar was produced (b). The tibial bone was fixed to this metal bar (black arrows) with screws in order to rule out additional extra-articular movement



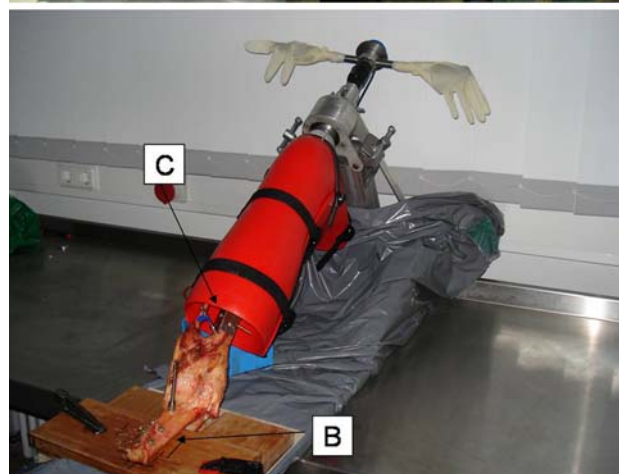
**Fig. 3** The Rotameter testing device: The lower leg is fixed in the custom-made Rotameter boot (A). At the handlebar (B) which is fixed to apply different torques is an electronic sensor to evaluate the inclination angle (DR. SCHETTER BMC Puchheim, Germany) (C) with an accuracy of  $0.01^\circ$ . The registration of the torque is given with an electronic torque key. The measured inclination angle and the applied torque can be seen digitally at the device (D) and is furthermore transmitted to a computer system

#### Statistical analysis

Statistical analysis was performed on SPSS 11.5 for Windows software. Statistical testing for parametric variables was used. The Pearson correlation coefficient was used to compare different measurement methods. It was deemed to show a reliable correlation if the Pearson coefficient was  $\geq 0.80$ . All rotational measurements were given in mean  $\pm$  SD.

#### Results

Three cadaver knees were excluded as they could not be adequately fixed to the ground because of poor bone quality. The remaining 17 of 20 knees could be successfully measured with both measurement methods at all applied torques.

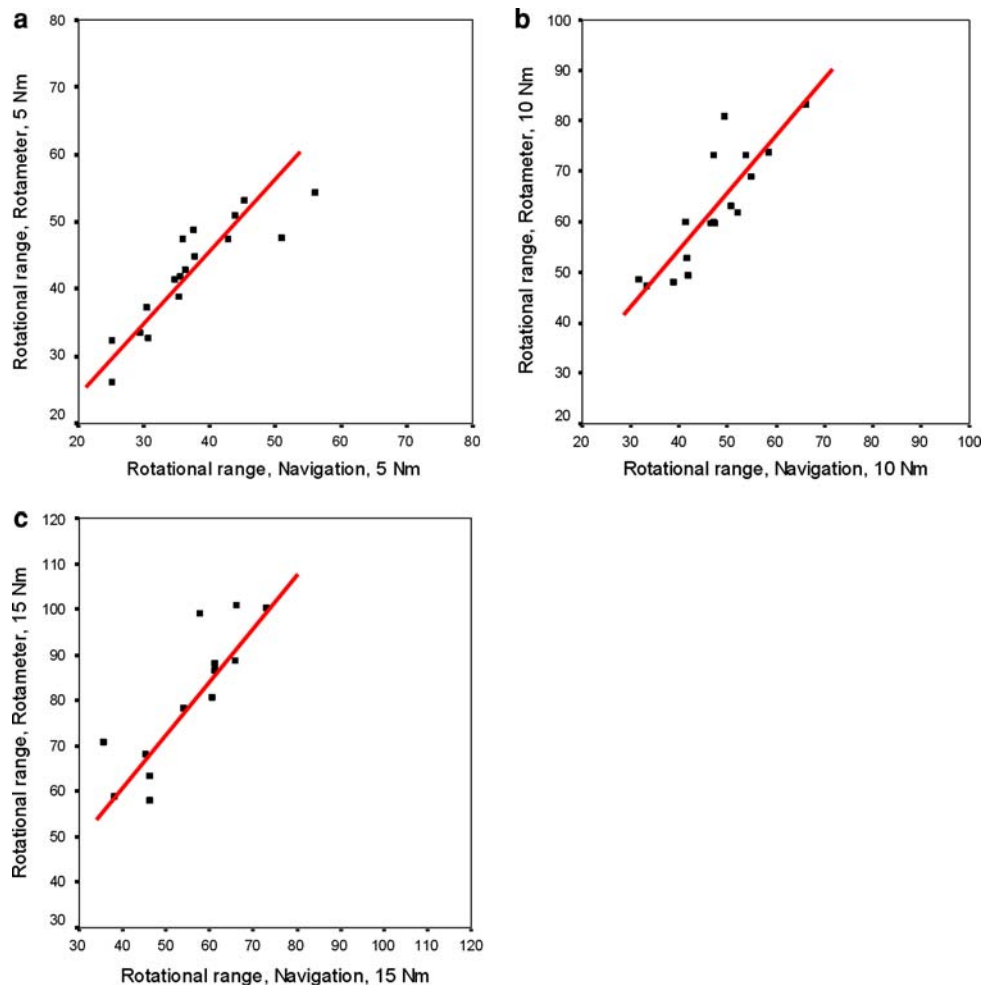


**Fig. 4** The Rotameter with a cadaver knee is prepared for the measurements. The pins with the infrared trackers (A) were bicortically fixed to the femoral and the tibial bone of the cadaver knees. The femoral bone was fixed to the ground and the (B) tibial bone was fixed to the custom-made inside-boot (C)

In both measurement methods, the rotational angle highly increased with the applied torque.

Comparison of the values measured of the Rotameter and the knee navigation revealed high Pearson correlation coefficient at all applied torques for internal rotation,

**Fig. 5 a–c** Scatter plots showing high correlation between the different measurement methods at 5, 10 and 15 Nm of applied torque



external rotation and the entire rotational range (internal plus external rotation) (Fig. 5a–c).

#### External rotation

At 5 Nm of applied torque,  $20.3^\circ \pm 6.9^\circ$  was measured with the Rotameter, the knee navigation showed  $17.3^\circ \pm 6.9^\circ$ . At 10 Nm,  $30.9^\circ \pm 9.5^\circ$  was found for the Rotameter, respective  $22.5^\circ \pm 8.0^\circ$  with the navigation. The highest applied torque of 15 Nm measured  $41.0^\circ \pm 12.1^\circ$  with the Rotameter and  $26.8^\circ \pm 8.8^\circ$  with the knee navigation.

A Pearson correlation coefficient of 0.95 was found at 5 Nm. At 10 Nm of applied torque, the Pearson coefficient was 0.90, and at 15 Nm, a Pearson coefficient of 0.90 was calculated.

#### Internal rotation

At 5 Nm,  $22.1^\circ \pm 8.0^\circ$  was measured with the Rotameter, the knee navigation showed  $18.9^\circ \pm 8.5^\circ$ . At 10 Nm,  $31.7^\circ \pm 9.8^\circ$  was found with the Rotameter, respective

$24.7^\circ \pm 9.4^\circ$  with the navigation. At 15 Nm of applied torque,  $39.2^\circ \pm 8.8^\circ$  was measured with the Rotameter and  $27.9^\circ \pm 8.4^\circ$  with the knee navigation.

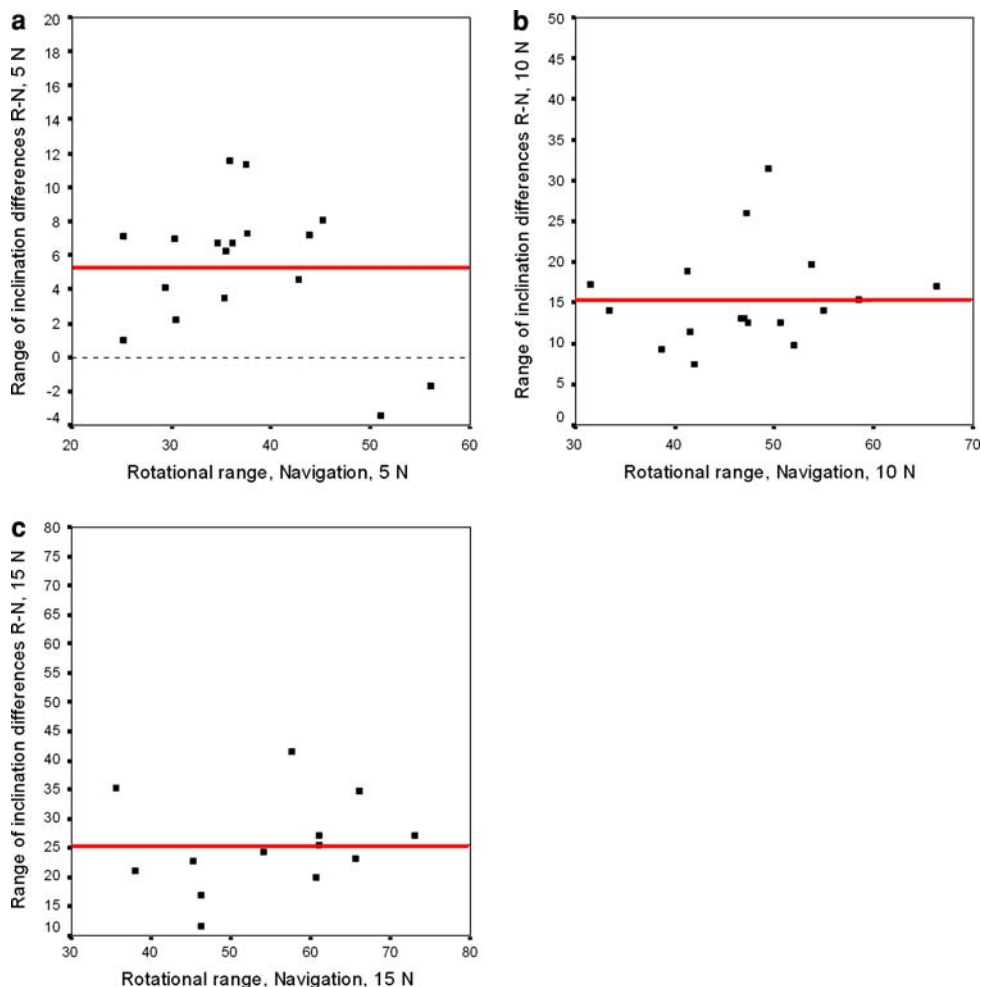
The calculated Pearson correlation coefficient was 0.87 at 5 Nm, at 10 Nm of applied torque, a Pearson coefficient of 0.93 was seen and at 15 Nm, the calculated Pearson coefficient was 0.90.

#### Entire rotational range

At 5 Nm of torque, the entire rotational range was  $42.5^\circ \pm 15.0^\circ$  with the Rotameter and  $37.2^\circ \pm 15.4^\circ$  with the knee navigation. At 10 Nm,  $62.6^\circ \pm 19.3^\circ$  of entire rotational range was measured with the Rotameter and  $47.2^\circ \pm 17.4^\circ$  with the knee navigation. At 15 Nm of applied torque,  $80.2^\circ \pm 20.9^\circ$  was found with the Rotameter, the knee navigation showed  $54.7^\circ \pm 17.2^\circ$  of entire rotational range.

The calculated Pearson correlation coefficient was 0.88 at 5 Nm and 0.85 at 10 Nm of applied torque. At 15 Nm, the Pearson coefficient of 0.86 was seen.

**Fig. 6 a–c** Bland–Altman plots showing the range of inclination differences in correlation with the rotational range at 5, 10 and 15 Nm of applied torque. The mean differences of the two measurement methods in the rotational range of 5°, 15° and 25° were statistically independent of the rotational angle (*red lines*)



## Discussion

The most important finding of the study represented in the results is that the comparison of the Rotameter compared with the invasive knee navigation system showed a high correlation in the Pearson coefficient.

As the device has already demonstrated a high inter- and intra-observer reliability, it may be of great importance to investigate tibial rotation to determine the restoration of the rotational stability of the knee after surgical procedures. It may also be valuable in detecting soft tissue injuries.

Previous studies using electromagnetic sensors or skin markers in their external rotational measurements reported difficulties in possible movement of their markers.

Kubo et al. [9] reported motion between the bones and the sensors attached to the skin by plastic braces. Georgoulis et al. [5] also reported their main limitation with regard to the movement of skin markers and their lack of the ability to predict bone locations.

Our device has neither skin markers nor sensors which might influence the results by accidental movement. Furthermore, the measured results of the Rotameter are not

influenced by determining the bone landmarks which might be demanding especially in obese patients. Since the use of a knee navigation to investigate knee kinematics has shown to be an accurate method [3, 17, 18, 21], the verification of our device was compared with the results of a knee navigation system. Pearle et al. [17] evaluated the reliability of a computer-assisted navigation system in determining multiplanar knee motion during in vitro cadaveric testing. They concluded that a knee navigation system reliably measures knee rotations during instrumented testing and correlated well with a robot sensor. Robinson et al. [18] used a navigation system to evaluate the function of the anteromedial and posterolateral bundles and reported that computer-assisted navigation allowed quantitative assessment of the effect of ACL reconstruction. Steckel et al. [21] investigated the kinematics of the intact ACL, single-bundle and double-bundle ACL reconstructions using an optical navigation system. They concluded that computer navigation allows evaluation of kinematics and a precise description of motion patterns in different knee conditions. Colombet et al. [3] also used knee navigation in the investigation of knee kinematics. They concluded that

computer-assisted navigation could provide a practical method to objective measurements.

Regarding our results in comparison with the knee navigation, our device showed an increased rotation especially at higher torques.

Since the normal range of rotation of the knee in various healthy populations *in vivo* is not known [1], it is difficult to compare the findings of our results. Only, a few *in vivo* measurements of tibial rotation have been reported [1, 4, 12, 15, 19, 20, 25]. Almquist et al. [1] evaluated the results of tibiofemoral rotation using also an external device and compared their results with their RSA measurements. They selected a knee flexion angle of 60° and 90° and an applied torque of 3, 6 and 9 Nm. At 9 Nm of applied torque, the results for the range (internal plus external rotation) were 65° ± 7° at 60° (66° ± 15° at 90°) for their external device and 28° ± 8° (32° ± 9°) for the RSA measurements. For the internal rotation, they reported 31° ± 3° (30° ± 9°) for their external device and 13° ± 4° (13° ± 5°) for the RSA method. For the external rotation, they found 36° ± 7° (34° ± 5°) for the external device and 19° ± 8° (15° ± 6°) for the RSA method. Zarins et al. [25] measured knee rotation with the patient lying on the side at different flexion angles. However, the applied torque was not reported and Shoemaker et al. [19] reported a range of 73° ± 20° at 20° of flexion at 10 Nm of applied torque. The literature further described a rotational range of 18°–27° [6, 7, 12, 20, 22] at 5 Nm of torque and 20°–30° of knee flexion.

In comparison to these results, our measurements showed at 5 Nm of torque a rotational range of 42.5° ± 15.0° for the Rotameter and 37.2° ± 15.4° for the knee navigation which was slightly higher. At 10 Nm of torque, 62.6° ± 19.3° was found for the Rotameter. This seems to be comparable with the results of the devices of Shoemaker [19] and Almquist [1]; 47.2° ± 17.4° was found for the knee navigation at 10 Nm torque in our setting.

Almquist et al. [1] also found increased differences in tibial rotation with an increasing torque with their measurement device compared with RSA measurements. The difference varied between 12° ± 7° and 35° ± 15° according to the flexion angle and applied torque. These findings were also confirmed in our findings.

This measurement error might have an influence on the measured tibial rotation. Comparing our measured rotation values and the reported values in the literature, the measured internal and external rotation values seemed to be highly dependent on the flexion angle and the applied torque [1, 19–21, 25]. There were also great differences in the total values according to the used method and especially to the used external device. Neither our device nor

other external devices in previous studies seem to show the exact rotational values.

However, the correlation between the two different methods in our study was high and as the differences in the measurements were constant at repeated measurements with a linear increase with increasing torque, the measurement error was systematic and can be predicted and compensated (Fig. 6a–c).

Our device demonstrated high inter- and intra-observer reliability even during *in vivo* measurements and high correlations comparing the measured knee rotations with the measurements of the contralateral knee [11]. As the measurement error of our device was constant and the device further showed a high correlation in the Pearson correlation coefficient compared with the navigation system, it may be of great value in the clinical use in order to determine tibial rotation after knee injuries or the restoration of rotational stability after surgical procedures especially in comparing it with the healthy contralateral side or with the measurements before surgery. Further investigation will show whether it might also be possible to assess the measurement error according to the applied torque and thus automatically correct the measured value of the device mathematically.

Using a knee navigation system with bicortically inserted pins as described in our study seems to be a reliable method to investigate knee rotation. However, as it is an invasive method, it is limited to biomechanical testing or small patient groups. Therefore, a non-invasive method might be of great value in the investigation of knee rotation.

A limitation of the study is the limited number of specimen which could be examined. Furthermore, no complex rotatory movements can be investigated and only rotational angles in 30° of flexion can be measured. No information can be obtained from other flexion angles. As the anteromedial (AM) bundle of the ACL tightens and the posterolateral (PL) bundle of the ACL relaxes in flexion, whereas in extension the PL bundle tightens and the AM bundle relaxes [10], this might have a significant influence on the results when the ACL is examined.

Cadaver investigations have demonstrated that both the AM and the PL bundles show their maximum shortening peak at 30° of flexion [26]. Therefore, this might be a sensitive flexion angle to detect possible influences of both bundles on tibial rotation. Furthermore, 30° of flexion in our device was also chosen as ACL injuries mostly occur in slight flexion angles.

The measurement device is currently involved in several clinical studies especially after ACL reconstruction and total knee replacement to further evaluate *in vivo* knee kinematics.

## Conclusion

The Rotameter testing device was able to show high correlations in the measurement of the external and internal rotation compared with an invasive knee navigation system. It might be used in a wide field as a valuable and non-invasive tool to investigate knee rotation.

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**Conflict of interest statement** No potential conflicts of interests are declared.

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