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Validity of an instrumented knee brace compared to 3D motion navigation: a cadaveric investigation

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1 **Title**

2 Validity of an instrumented knee brace compared to 3D motion navigation: a cadaveric  
3 investigation

4 **Abbreviated title**

5 Validity of an instrumented knee brace

6 **Authors**

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24

**Highlights :**

25

- Reliability of an instrumented knee brace during specific tasks

26

- Consideration of soft tissue artifacts on knee brace with cadaveric navigation

27

- Validity of 3 axis kinematics of instrument knee brace compare to navigation investigation

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31 **1. Abstract**

32 The aim of this study was to test the accuracy and the reliability of 3-dimensional angular  
33 measurements of an instrumented knee brace compared to the gold standard navigation system  
34 optoelectronic cameras-based.

35 Thirteen cadaveric bodies were used to calculate kinematic knee parameters. Three exercises  
36 were performed, 100° flexion (FLEX100), internal/external rotation with a 30° flexion  
37 (ROT30), and the pivot shift test (PS).

38 The reliability was excellent with an ICC (95%) > 0.90. The agreement between the two  
39 systems showed excellent correlation in the F/E axis for FLEX100 and PS ( $\sigma_{(Flex/Ext)} > 0.95$ )  
40 and strong correlation in the I/E axis for ROT30 ( $\sigma_{(Rot Int/Ext)} > 0.939$ ). The root mean square  
41 error (RMSE) was under 5° for all exercises considering the soft tissue artifact (STA) for the  
42 F/E axis.

43 Consequently, the instrumented knee brace exposed high reliability and accuracy which could  
44 end up on clinical interpretations thanks to the previous measures.

45 **2. Keywords**

46 Connected knee brace, inertial measurement unit, joint kinematics, navigation, validity,  
47 reliability

48

### 49 **3. Background**

50 Knee joint function can be altered by several pathologies, such as anterior cruciate ligament  
51 rupture (ACLR) and knee osteoarthritis (OA) [1–4]. A better understanding of knee pathologies  
52 has given rise recently to new knee diagnostic and analysis tools [5–7]. Thus, motion capture  
53 and questionnaires have become the gold standard for practitioners for several pathologies  
54 [1,2,8]. The optoelectronic camera system (OCS) is the usual tool for quantifying body motion  
55 [2,9–11]. However, motion capture with OCS has few limitations. Firstly, the gait patterns can  
56 be affected by the laboratory environment compared to an ecological environment [12–14].  
57 Secondly, the OCS is very expensive, restricted to a limited field of view in time and space  
58 [12,14] and time consuming. Finally, the OCS cannot be used in a home-based rehabilitation  
59 perspective.

60 To develop systems that overcome these disadvantages, recent research has focused on gait  
61 analysis using wearable sensors [15], and new systems have been developed to quantify human  
62 motion. For example, accelerometers are valid and reliable for the recording of activity, energy  
63 expenditure and acceleration data [16]. Nevertheless, the precision of kinematic measurements  
64 is poor with an accelerometer sensor only due to the presence of drift during fast accelerations  
65 [17,18]. Combining a gyroscope with an accelerometer may solve this problem. Indeed,  
66 gyroscopes can estimate sensor orientation by integrating the angular velocity on the X, Y, Z  
67 axes relative to the sensor. Yet this sensor is subject to a drift in angular velocity due to signal  
68 integration, a well-known problem in robotics and motion analysis. By mixing the  
69 complementary data from accelerometers and gyroscopes, the two drifts can be minimized with  
70 a fusion algorithm like a Kalman filter [16,19,20]. The association of the two sensors is called  
71 an inertial measurement unit (IMU). Body sensor networks with IMUs such as Xsens MVN  
72 (Xsens Technologies BV, Enschede, NL) [21] or Perception NEURON Pro (Noitom, Miami,  
73 FL, USA) [22] provide quantitative movement analysis in ecological environments.

74 In a home-based rehabilitation perspective, the knee motion analysis has become necessary to  
75 supervise patients through biofeedback. To deal with that, a new instrumented knee brace with  
76 two IMUs was developed. These sensors calculated the movement of the thigh relative to the  
77 shank. Moreover, this integrated system compares to simple IMU sensors described previously  
78 did not necessitate clinicians or physiotherapist for calibration or anatomical placement due to  
79 its ease of use. Indeed, once the connected knee brace is in place, it is possible to quantify knee  
80 motion in an ecological environment to reduce bias in laboratory conditions with a smartphone  
81 [23–25]. Palpation to find anatomical landmarks is not required, nor is it necessary to fix  
82 markers or IMUs with different systems, as it is the case with other systems [2,26]. Moreover,  
83 this technology offers free use of a workstation for motion computation through cloud  
84 computing on the smartphone app, and biofeedback can be displayed in real time with  
85 smartphone computation. All these data allow a quantified rehabilitation for physiotherapists  
86 or clinicians via success scores and pain scale charts. Then, this system enhance physical  
87 rehabilitation by motivating the user with visual data of progression and informative videos  
88 [27].

89 However, this knee brace, like IMU systems or OCS, is sensitive to soft tissue artifacts (STA),  
90 a problem inherent to all skin-mounted tracking system. A systematic review noted the effects  
91 of STA in the lower limb, finding that several factors influence the results, including sensor  
92 orientation [28]. STA was found to reach more than 30 mm of magnitude on the thigh segment  
93 and more than 15 mm on the tibia [28]. To overcome this problem, OCS investigation with  
94 bony pins would be highly accurate [29,30], but this procedure is unethical and should not be  
95 applied to living patients. Along the same lines, the fluoroscopic 3D-matching technique is  
96 invasive due to radiation exposure [31]. Recently, several studies have used commercial  
97 navigation devices to assess knee kinematics during surgical procedures for ACL reconstruction  
98 or total knee arthroplasty [32–34]. Navigation is composed of three parts: computer platform,

99 tracking system, and rigid body marker. Tracking system visualizes the rigid body markers  
100 through OCS and calculates motion in real time with the tracking systems. Markers are fixed to  
101 the patient's bones surgical instruments to track joint motion or target objects after a referencing  
102 procedure which consists in determining bone positions compared to marker positions [35]. For  
103 example, this system via bony pins and OCS is a computer-assisted surgical navigation device  
104 to help tunnel placement during ACL reconstruction and can quantify knee laxity and validate  
105 the surgical procedure [33,36].

106 A more ethical solution might be considered to begin with cadaveric investigations. Indeed,  
107 tibiofemoral motion in the unloaded cadaveric knee is almost the same as that in the living knee  
108 [37,38].

109 Given the innovative aspect of the knee brace, its accuracy and reliability must be confirmed  
110 before the system can be used more extensively. In the present study, we thus investigated the  
111 accuracy and reliability of this new system of knee motion quantification and compared it to  
112 the gold standard during specific movements well-known to physiotherapists and orthopedic  
113 surgeons.

114

## 115 **4. Material and methods**

### 116 **4.1. Subjects**

117 Thirteen intact knees from seven frozen cadaveric males were used for this study. The  
118 specimens were thawed at room temperature for at least three hours and they showed no sign  
119 of degeneration. Exclusion criteria were signs of knee instability (Lachman test) and signs of  
120 surgical procedures on knee or hip, evidence of a knee or hip prosthesis, ACL reconstruction,  
121 etc. The mean age of the specimens was approximated at 85 years-old approximately due to a  
122 lack of anthropological information.



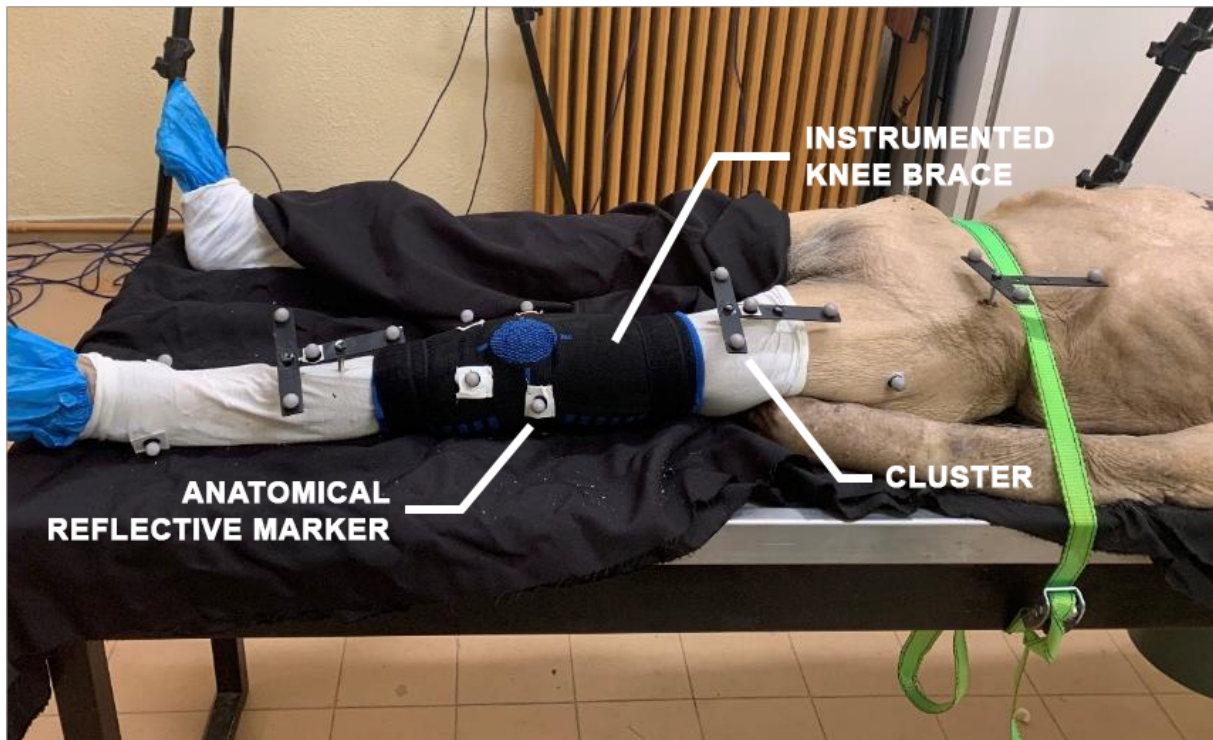
## 4.2. Material and instrumentation

123  
124 Three clusters of four reflective markers were fixed by one screw on the pelvis and two screws  
125 on the femur and tibia to record the knee kinematics. The femoral and tibial screws were fixed  
126 in the bone diaphysis outside the joint capsule with a 2-cm incision to avoid influencing the soft  
127 tissue. After fixing the three clusters, seven anatomical landmarks were identified with  
128 reflective markers fixed onto the skin with cyanoacrylate glue. The medial malleolus (MM),  
129 the lateral malleolus (LM), the medial and lateral epicondyle of the femur (MF, LF), the medial  
130 and lateral epicondyle of the tibia (MT, LT) and the greater trochanter (GT) were located.  
131 Kinematic data were simultaneously obtained with seven cameras (Vicon Motion Systems Ltd.  
132 Oxford, UK): four MX-T20 and three MX-T40 and with the instrumented knee brace with a  
133 sampling frequency of 100 Hz. The instrumented knee brace is composed with two IMU ICM-  
134 20948. The knee sleeve was designed to reduce compression around the knee by using soft  
135 tissue in opposition to medical knee sleeve designed to change the knee joint kinematic [39].  
136 The knee sleeve compression around the knee was minimal to avoid change in knee joint  
137 movement but enough to limit the movement of the IMU sensors. IMU's knee brace had a 16  
138 bits resolution for accelerometers and gyroscope. However due to Bluetooth Low Energy  
139 communication, these resolutions were downgrade to 10 bits with respectively, a sensitivity of  
140 7.81 mg/LSB for a  $\pm 4$  g range and a sensitivity of 0.98 dps/LSB for a range of  $\pm 500$  dps.

141

142

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144

145 **Figure 1:** View of the instrumented knee brace, reflective markers and clusters placement on  
146 the cadaver's lower limb. The torso was strapped to the table to minimize artifacts on the hip  
147 cluster position.

148

### 149 **4.3. Experimental protocol**

150 To evaluate the position of the clusters relative to the bones, a functional movement protocol  
151 was generated with the leg extended on the table in a static position then with the leg fully  
152 extended realizing hip circular movement. The hip joint can be modeled as a ball-and-socket  
153 joint, and the hip joint center (HJC) location is characterized by a point invariant in any position  
154 of the joint [40]. The coordinates of the femoral head location were obtained by an optimization  
155 method to minimize the HJC movement in the circle movements compared to the hip reference.  
156 The distal femur location was determined at the middle of the MF and LF markers. The  
157 proximal and distal tibia locations were calculated between the MT and LT markers and the  
158 MM and LM markers, respectively.

159 The mechanical axis of the femur was defined by the line containing the femoral head location  
160 and the distal femur location. The femoral condylar axis was defined by the MF and LF markers.  
161 The femoral frontal plane was defined by the plane containing the mechanical axis and the  
162 femoral condylar axis. The femoral sagittal plane was defined with the femoral axis and the  
163 cross-product of the femoral axis and the femoral condylar axis [40]. The mechanical axis of  
164 the tibia was defined by the line containing the proximal and distal locations of the tibia. The  
165 tibial condylar axis was defined by the MT and LT markers. The tibial frontal plane was defined  
166 by the plane containing the mechanical axis and the tibial condylar axis. The tibial sagittal plane  
167 was defined with the tibial axis and the cross-product of the tibial axis and the tibial condylar  
168 axis. To estimate the orientation of the two IMUs of the instrumented knee brace, we used a  
169 procedure implemented in a smartphone application.

170 The operator performed four movements, five times each: a flexion with a full extension to  
171  $100^\circ$  of flexion (FLEX100), a maximal internal/external rotation with a flexion of  $30^\circ$  (ROT30),  
172 a pivot shift test (PS) and a flexion from full extension to maximal knee flexion under constraint  
173 (FLEXMAX).

174

## 175 **5. Calculation**

### 176 **5.1. Analysis**

177 The synchronization of the two systems was performed by a wand with three reflective markers  
178 on it. The maximum acceleration detected when the wand hit the thigh IMU was synchronized  
179 with the trajectory of the wand's reflective markers. Data from the OCS were analyzed and the  
180 angles were computed in Python. The data from the instrumented knee brace were collected  
181 and the angles were computed in Python with a data fusion algorithm based on Valenti et al.  
182 filter applied to the accelerometric and gyroscopic data [20]. However, data analysis revealed  
183 problems with the calibration protocol for the instrumented knee brace due to the dorsal

184 decubitus position of the cadavers. A better alternative estimation was to find the IMU  
185 orientation by comparing clusters and IMU movements when there were small flexions in  
186 FLEXMAX. This estimation of the IMU orientation was used for all other exercises. Then,  
187 some acquisitions were not processed because of the abnormal movement of some of the  
188 anatomical marker fixed on the knee brace (MF, LF, MT and LT), which resulted in the  
189 selection of only 23 acquisitions in all. Due to motion differences between operators, only 13  
190 acquisitions for pivot shift test were selected among the 23.

## 191 **5.2. Statistical analysis**

192 Statistical analysis was performed on the FLEX100, ROT30 and PS exercises. The variables  
193 extracted for reliability were the intraclass correlation coefficient (ICC) and Bland & Altman  
194 plots. ICC was considered poor ( $<0.50$ ), moderate (between 0.5 and 0.75), good (between 0.75  
195 and 0.90), or excellent ( $>0.90$ ) [41]. The variables extracted for validity were Pearson's  
196 correlation coefficient ( $\sigma$ ), the root mean square error (RMSE), and the mean confidence  
197 interval (CI). Pearson's coefficient was evaluated as excellent ( $>0.95$ ), very good (0.85-0.95),  
198 good (0.75-0.85), moderate (0.65-0.75) or weak ( $<0.65$ ) [42]. Error (RMSE)  $<5^\circ$  was  
199 considered excellent, and between 5 and  $10^\circ$  it was considered good [16]. RMSE was measured  
200 without offset on the abduction/adduction (A/A) axis and the internal/external rotation (I/E)  
201 axis because of the poor accuracy of the alternative IMU orientation procedure. To deal with  
202 STA [43], we extracted two types of variables for the validity: the validity on the standard knee  
203 motion and the validity on the knee motion with consideration of STA on the flexion/extension  
204 (F/E) axis through a linear regression on FLEXMAX acquisitions.

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209 **6. Results**

210

211 The ICC (95%) for the kinematic parameters recorded with the instrumented knee brace showed  
 212 excellent reliability for all exercises. In terms of concurrent validity, Pearson’s r coefficient for  
 213 the instrumented knee brace kinematics compared to the navigation kinematics showed the  
 214 following for all exercises: very good to excellent correlations for the F/E angles, poor to  
 215 excellent correlations for I/E rotation, and poor to excellent correlation for A/A (Table 1).  
 216 RMSE was less than 5° between systems except for the F/E axis. Table 2, Figure 3, Figure 4  
 217 and Figure 5 show the impact of STA. The Bland & Altman plots showed the difference in the  
 218 range of motion (RoM) between the two systems (Figure 2). 3D kinematics of the knee during  
 219 the three exercises are depicted in Figure 3, Figure 4, and Figure 5. Rates of flexions for  
 220 FLEX100 and PS were  $78.3 \pm 12.4$  dps and  $55.5 \pm 8.9$  dps, rates of rotations for ROT30 were  
 221  $19.4 \pm 2.8$  dps. Coefficients of variation (CV) were respectively: 15.8%, 16.0%, 14.3%.

222 **Table 1.**

223 ICC and Pearson’s correlation coefficient ( $\sigma$ ) between instrumented knee brace and navigation.  
 224 (CI = confidence interval.)

225

Exercise	FLEX100	ROT30	PS
ICC (CI 95%)	0.979 (0.959 – 0.990)	0.957 (0.918 – 0.980)	0.976 (0.944 – 0.992)
$\sigma_{(F/E)}$ (CI 95%)	0.999 (0.999 – 0.999)	0.888 (0.794 – 0.981)	0.991 (0.984 – 0.997)
$\sigma_{(I/E)}$ (CI 95%)	0.700 (0.621 – 0.780)	0.956 (0.939 – 0.972)	0.725 (0.506 – 0.944)
$\sigma_{(A/A)}$ (CI 95%)	0.820 (0.723 – 0.917)	0.649 (0.624 – 0.895)	0.860 (0.789 – 0.931)

226

227

228 **Table 2.**

229 RMSE of F/E, F/E with STA regression, I/E, and A/A with 95% confidence interval

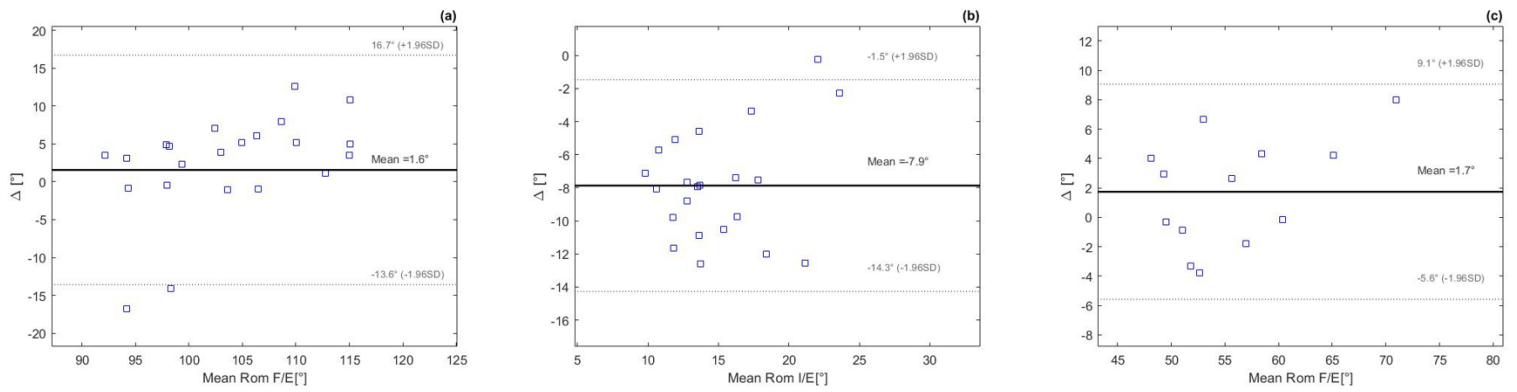
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Exercise	FLEX100 (°)	ROT30 (°)	PS (°)
F/E (CI 95%)	8.26 (6.77 – 9.77)	4.65 (3.11 – 6.18)	6.06 (4.86 – 7.27)
F/E Reg (CI 95%)	2.96 (2.31 – 3.61)	1.01 (0.83 – 1.20)	2.72 (2.08 – 3.35)
I/E (CI 95%)	2.25 (1.99 – 2.52)	3.12 (2.67 – 3.58)	3.89 (3.03 – 4.75)
A/A (CI 95%)	3.82 (3.25 – 4.38)	1.83 (1.57 – 2.10)	3.53 (2.45 – 4.61)

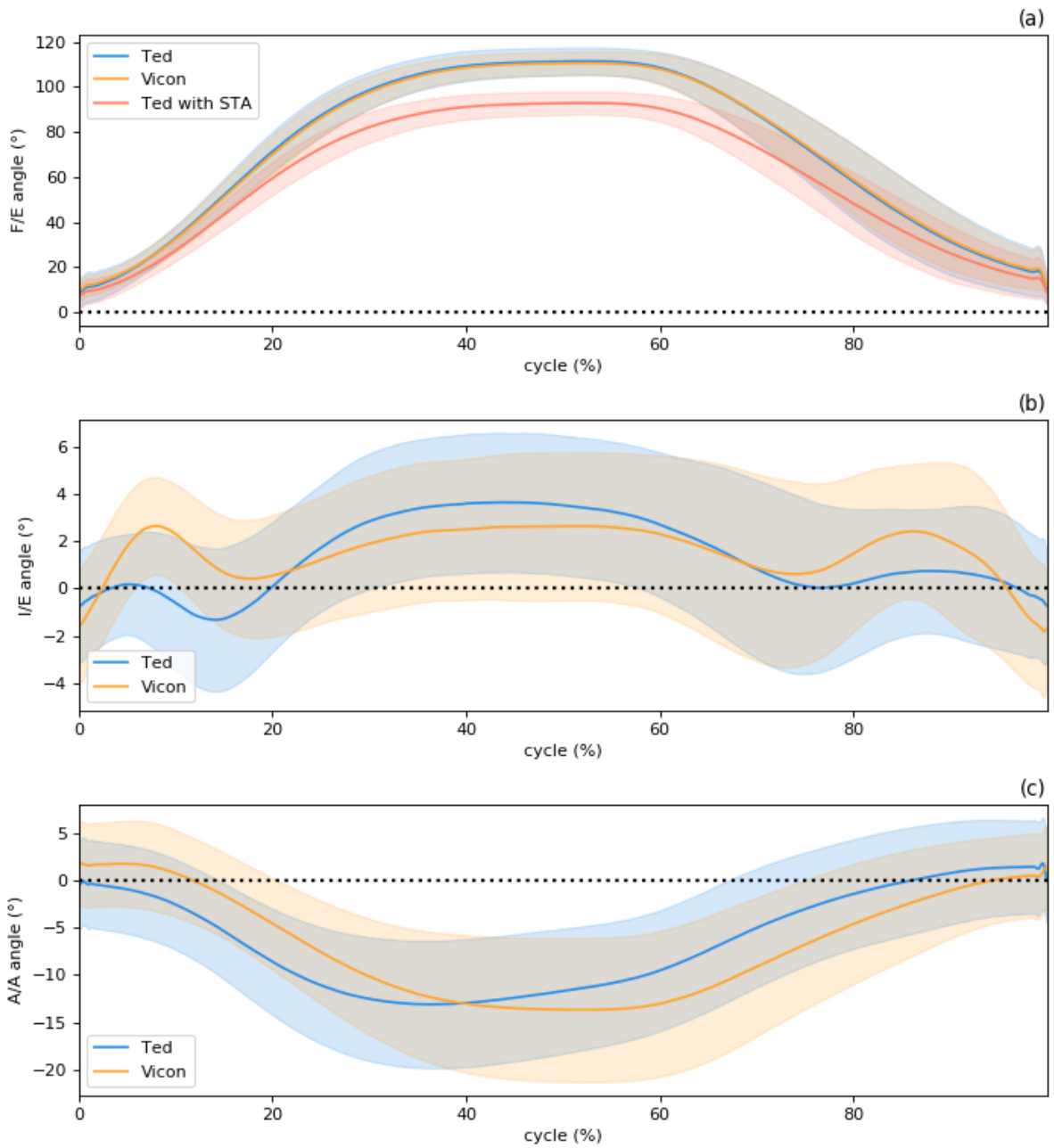
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234 **Figure 2:** Bland & Altman plots of RoM from both systems for FLEX100 (a), ROT30 (b) and  
235 PS (c). Each graph represents the mean difference (black line) and the CI 95% of the  
236 difference (dashed lines) as recorded by the instrumented knee brace and navigation.

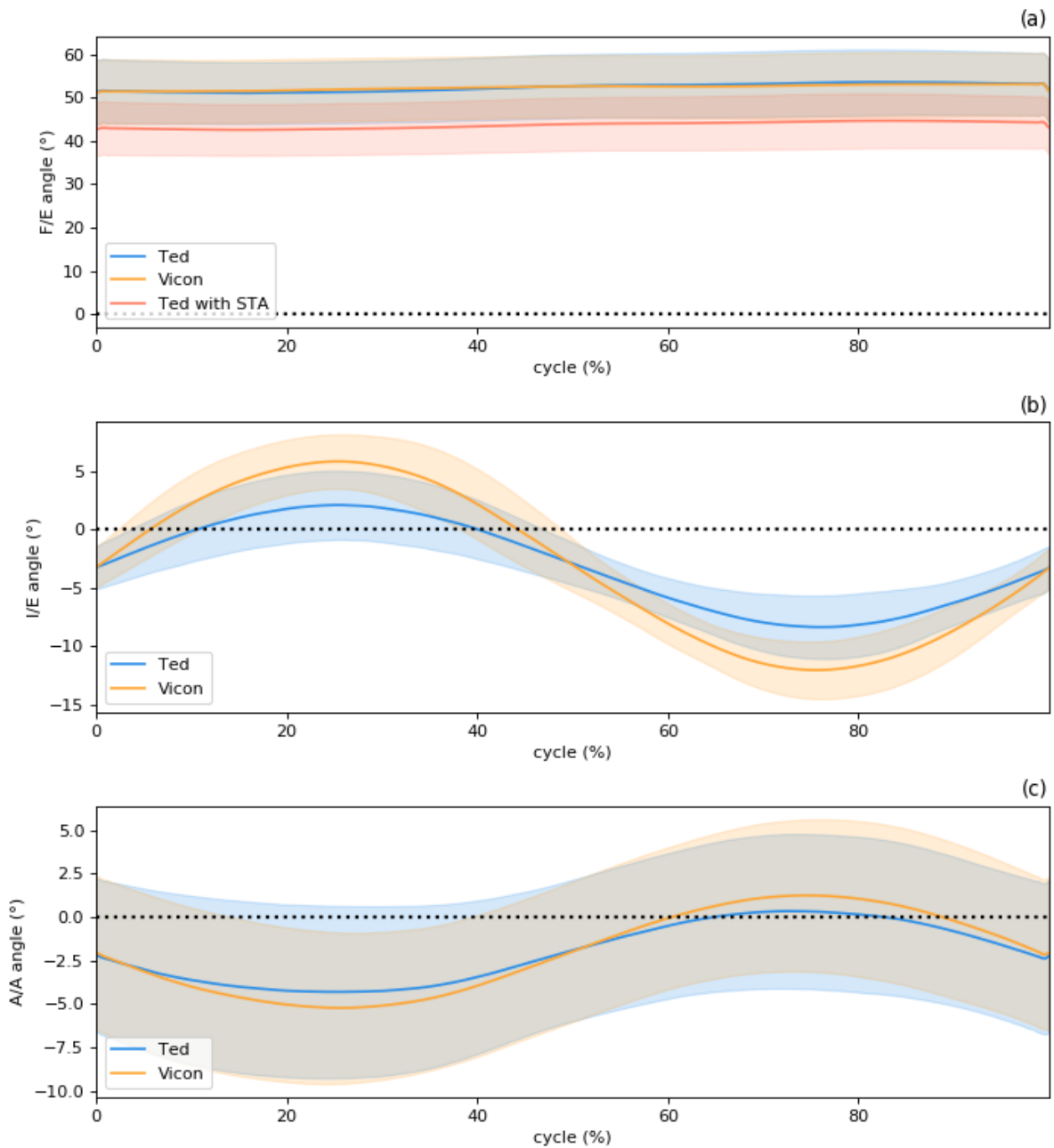


237  
 238 **Figure 3:** Mean knee joint kinematics over all trials and all subjects with a standard deviation  
 239 cloud to compare the two systems (Instrumented knee brace in blue, Instrumented knee brace  
 240 without STA regression in red, Navigation with Vicon in orange) for flexion 100° in F/E (a),  
 241 I/E (b), A/A(c)

242

243

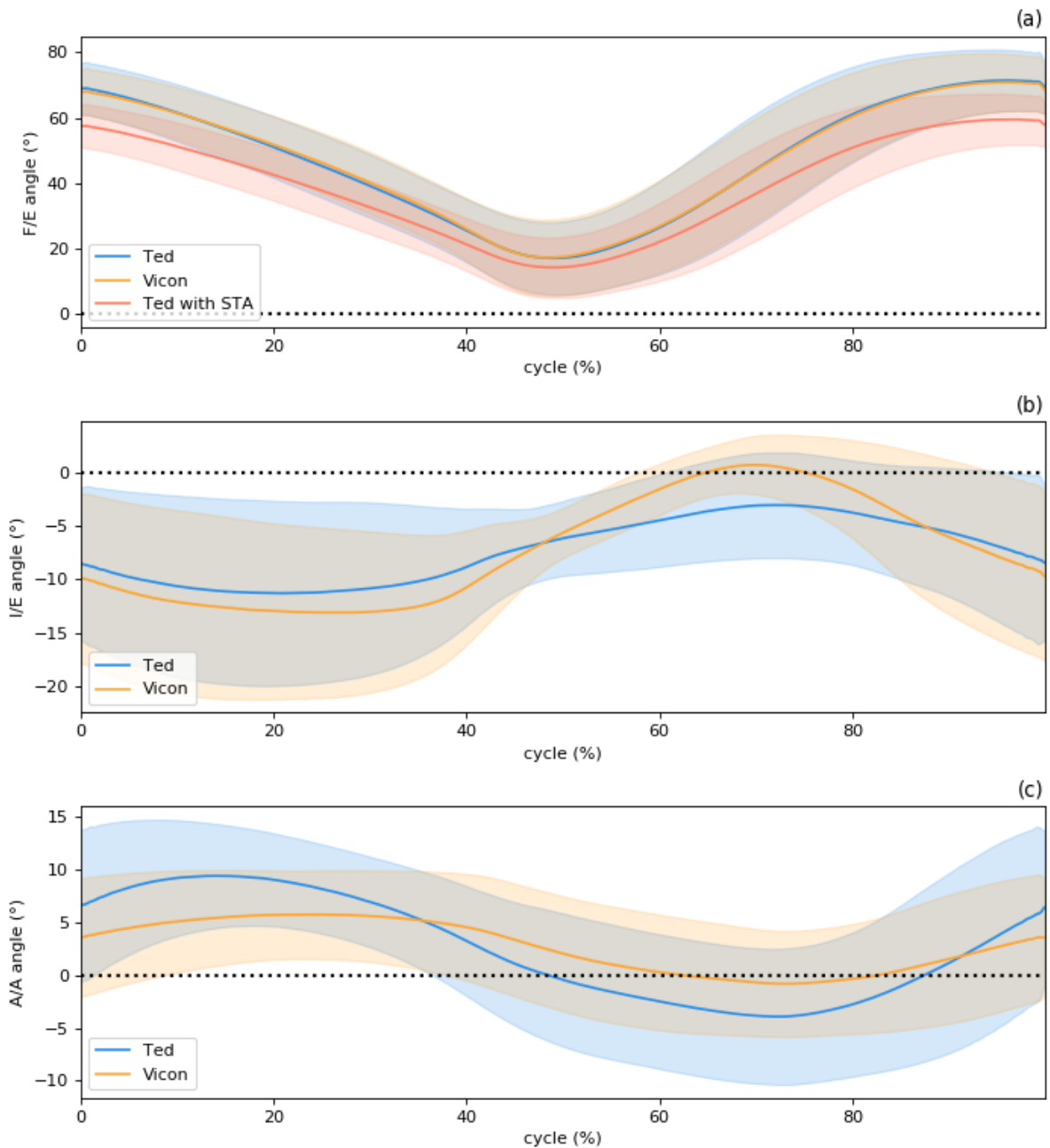
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245  
 246 **Figure 4:** Mean knee joint kinematics over all trials and all subjects with a standard deviation  
 247 cloud to compare the two systems (Instrumented knee brace in blue, Instrumented knee brace  
 248 without STA regression in red, Navigation with Vicon in orange) for internal/external rotation  
 249 at 30° of flexion in F/E (a), I/E (b), A/A(c)

250





251  
 252 **Figure 5:** Mean knee joint kinematics over all trials and all subjects with a standard deviation  
 253 cloud to compare the two systems (Instrumented knee brace in blue, Instrumented knee brace  
 254 without STA regression in red, Navigation with Vicon in orange) for pivot shift test in  
 255 extension in F/E (a), I/E (b), A/A(c)

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## 260 7. Discussion

261

262 This study compared a new instrumented knee brace based on two IMU sensors aligned to the  
263 lateral side of the pelvis and the leg with an OCS to evaluate the accuracy and reliability of the  
264 new system during specific tasks. The study showed the excellent reliability of the knee brace  
265 and the strong concordance between the two systems. The difference in the RoMs was  
266 acceptable. The RMSE values of the OCS and the knee brace for the three angles remained  
267 under 5° for all exercises.

268 The reliability of the IMU system was tested for each exercise and demonstrated  $ICC > 0.918$   
269 for all exercises, indicating excellent reliability. Moreover, the results are in line with the  
270 literature. Indeed, the ICC of the FLEX100 exercise was similar to the results found by  
271 Maderbacher's study, which showed an ICC of 0.92 for knee flexion [44]. The results for I/E  
272 rotation with our knee brace were similar to those found by Musahl et al., who reported ICCs  
273 from 0.94 to 0.99 for measured rotational knee laxity with a noninvasive system [45]. Other  
274 studies of gait analysis using IMU systems have found similar results, with excellent reliability  
275 for the flexion angle [46,47]. These studies are consistent with findings of the excellent  
276 reliability of IMU systems for several tasks.

277 The correlations between the two systems were excellent in the major axis of each exercise.  
278 These results are in line with the Pearson's correlation coefficient of 0.96 reported by Kayaalp  
279 et al. and the agreement between 0.82 to 1.0, depending on the task, for knee F/E reported by  
280 Lebel et al. [42,48]. However, the correlations for the minor axes were not as conclusive with  
281 Pearson's correlation coefficients ranging from weak to excellent. Favre et al. brought this trend  
282 to light with measurements of IMUs and the knee exoskeleton during a gait test, finding the  
283 major axis  $\sigma = 1.00 (0.00)$  in F/E and the minor axes  $\sigma = 0.76(0.18)$  in A/A and  $\sigma = 0.85(0.11)$   
284 in I/E [49]. Then, additional measurements revealed agreement levels between poor and

285 excellent, depending on the axis and joint, for squats (SQ), single-leg squats (SLS) and  
286 countermovement jumps (CMJ). For the knee joint, the minor axes for these exercises showed  
287 less agreement, ranging from poor to excellent, compared to the major axis (F/E), which showed  
288 excellent agreement [43]. These findings underline the weaker correlation of the two minor  
289 axes of the knee and the strong correlation in F/E found in this study, except for the ROT30  
290 exercise due to a major axis in the I/E axis.

291 The accuracy of the instrumented knee brace as assessed by RMSE was under  $5^\circ$  in the three  
292 axes (F/E without STA). Lebel et al. reported comparable mean RMSE varying between  $1.1^\circ$   
293 and  $5.5^\circ$ , depending on the segment tracked and the task performed [48]. The same results were  
294 found by Kayaalp et al., with a mean RMSE of  $5.17^\circ$  in F/E during a gait test [42]. A systematic  
295 review by McGinley et al. confirmed these results and noted that most studies reported error of  
296 less than  $5^\circ$  for all gait variables, excluding hip and knee rotation [50]. The study by Robert-  
297 Lachaine et al. was in line with these results, with RMSE between  $3^\circ$  and  $6^\circ$  for knee rotations  
298 in the F/E, I/E, and A/A axes [51]. These authors thus agreed on the clinical relevance of IMU  
299 systems with RMSE values under  $5^\circ$ .

300 Bland & Altman analysis revealed a similar RoM with a mean error under  $2^\circ$  in F/E due to the  
301 STA regression used in the computation angles of the instrumented knee brace. These results  
302 are similar to the findings of Teufl et al. for SQ, SLS and CMJ with a mean error of  $2^\circ$  [43].  
303 Another study on Sit To Stand (STS) test with visual feedback showed a mean difference  
304 ranging from  $-1.7^\circ$  to  $3.2^\circ$  in the F/E axis between the IMU system and OCS [52]. More  
305 specifically, Leardini et al. highlighted a mean RoM error of  $3.9^\circ$  for knee flexion between  $0$  to  
306  $95^\circ$  [27]. However, the RoM error for our ROT30 exercise revealed an underestimation in the  
307 I/E rotation axis due to STA. Unfortunately, no significant regression was found to minimize  
308 STA on this axis. Indeed, Stagni et al. also observed a simple overestimated flexion in F/E but  
309 a more complex artifact for I/E and A/A rotations [53].

310 A few limitations of this study should be noted. First, the outcomes were marred by STA, which  
311 impacted each axis of rotation, but more specially the I/E and A/A rotations because there was  
312 no compensation for STA. More studies are required to identify the best approach to minimize  
313 STA and reduce RMSE between the connected knee brace and bone placement [31,54]. Indeed,  
314 the results of the ROT30 exercise contradicted the findings of Moewis et al. (Figure 2; Figure  
315 3), who suggested a linear overestimation of I/E rotation with skin-mounted markers compared  
316 to knee fluoroscopy [55,56]. Second, the alternative procedure for estimating the IMU  
317 orientation with optimization introduced inaccuracy into the measurement of I/E and A/A  
318 rotations due to the exercise of flexion used by the optimization algorithm [57,58]. In fact, the  
319 I/E and A/A rotations had a small range of motion and were in general less valid due to the  
320 projection of the F/E rotation, caused by small errors in IMU orientation estimation during the  
321 calibration phases [16,58,59]. Further studies should elucidate the most appropriate calibration  
322 methods to estimate joint kinematics [42,57]. Third, even if navigation system allows a motion  
323 capture without STA, mechanical properties between cadaveric and living knee may differ due  
324 to difference in soft tissue tension, capsule, ligaments and neglecting the influence of muscle  
325 contractions [38,60]. Then, passive kinematics may differ from active kinematics [38,60]. Not  
326 least of all, rates of flexion and rotation for FLEX100, PS and ROT30 highlighted limitations  
327 in reliability of movements due to a CV close to or even higher than 15% [61]. Acquisition  
328 performed with a robotic arm would acquire better data with repetitive ranges and rates [62].  
329 However, acquired data performed with clinicians is closer to field data acquisitions.

330

331 **8. Conclusion**

332

333 The present work investigated the reliability and accuracy of a new instrumented knee brace  
334 compared to a gold standard navigation system without STA. The new brace showed excellent  
335 reliability and sufficient accuracy for clinical interpretations. However, STA induced errors in  
336 the axes without artifact consideration algorithm. In conclusion, this study highlights the  
337 clinical validity of the instrumented knee brace. Further investigations are necessary to develop  
338 new algorithms to minimize STA in the I/E and A/A

339

340 **9. Declaration of competing interest**

341 The institutes of the Authors have received funding from the marketing company the  
342 instrumented knee brace Ted Orthopedics to cover the costs involved in the execution of this  
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344 Thelma, Puech Stephane, Ollivier Matthieu, Chabrand Patrick, Gerus Pauline have no  
345 proprietary, financial, professional or other personal interest of any nature of kind of any  
346 product, service and/or company that could be construed as influencing the position presented  
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348

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355 **11. References**

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- 357 [1] R. García-Bógalo, R. Larraínzar-Garijo, A.D. Murillo-Vizuate, J. Montoya-Adárraga, O.  
358 Marín-Peña, M. Pérez-España Muniesa, L. Horna-Castañeira, Evaluation of  
359 intraoperative anterior cruciate ligament laxity reconstruction &, *Rev Esp Cir Ortop*  
360 *Traumatol.* 56 (2012) 267–73. <https://doi.org/10.1016/j.recote.2011.12.003>.
- 361 [2] D. Bytyqi, B. Shabani, S. Lustig, L. Cheze, N. Karahoda Gjurgjeala, P. Neyret, Gait knee  
362 kinematic alterations in medial osteoarthritis: Three dimensional assessment, *Int.*  
363 *Orthop.* 38 (2014) 1191–1198. <https://doi.org/10.1007/s00264-014-2312-3>.
- 364 [3] S. Ren, Y. Yu, H. Shi, X. Miao, Y. Jiang, Z. Liang, X. Hu, H. Huang, Y. Ao, Three  
365 dimensional knee kinematics and kinetics in ACL-deficient patients with and without  
366 medial meniscus posterior horn tear during level walking, *Gait Posture.* 66 (2018) 26–  
367 31. <https://doi.org/10.1016/j.gaitpost.2018.08.007>.
- 368 [4] P. Ismailidis, C. Egloff, L. Hegglin, G. Pagenstert, R. Kernen, A. Eckardt, T. Ilchmann,  
369 A. Mündermann, C. Nüesch, Kinematic changes in patients with severe knee  
370 osteoarthritis are a result of reduced walking speed rather than disease severity, *Gait*  
371 *Posture.* 79 (2020) 256–261. <https://doi.org/10.1016/j.gaitpost.2020.05.008>.
- 372 [5] S.S. Paul, C.G. Canning, Five-repetition sit-to-stand, *J. Physiother.* 60 (2014) 168.  
373 <https://doi.org/10.1016/j.jphys.2014.06.002>.
- 374 [6] M. Ateef, S. Kulandaivelan, S. Tahseen, Test–retest reliability and correlates of 6-minute  
375 walk test in patients with primary osteoarthritis of knees, *Indian J. Rheumatol.* 11 (2016)  
376 192. <https://doi.org/10.4103/0973-3698.192668>.
- 377 [7] A. Gomez Bernal., R. Becerro-de-Bengoa-Vallejo, M.E. Losa-Iglesias, Reliability of the  
378 OptoGait portable photoelectric cell system for the quantification of spatial-temporal  
379 parameters of gait in young adults, *Gait Posture.* 50 (2016) 196–200.  
380 <https://doi.org/10.1016/J.GAITPOST.2016.08.035>.
- 381 [8] P. Devita, J. Aaboe, C. Bartholdy, J.M. Leonardis, H. Bliddal, M. Henriksen,  
382 Quadriceps-strengthening exercise and quadriceps and knee biomechanics during  
383 walking in knee osteoarthritis : A two-centre randomized controlled trial, *Clin. Biomech.*  
384 59 (2018) 199–206. <https://doi.org/10.1016/j.clinbiomech.2018.09.016>.
- 385 [9] T.A. Gerbrands, M.F. Pisters, B. Vanwanseele, Individual selection of gait retraining  
386 strategies is essential to optimally reduce medial knee load during gait, *JCLB.* 29 (2014)  
387 828–834. <https://doi.org/10.1016/j.clinbiomech.2014.05.005>.
- 388 [10] J. Favre, B.M. Jolles, Gait analysis of patients with knee osteoarthritis highlights a  
389 pathological mechanical pathway and provides a basis for therapeutic interventions,  
390 *EFORT Open Rev.* 1 (2016) 368–374. <https://doi.org/10.1302/2058-5241.1.000051>.
- 391 [11] L.D. Duffell, S.J. Jordan, J.P. Cobb, A.H. McGregor, Gait adaptations with aging in  
392 healthy participants and people with knee-joint osteoarthritis, *Gait Posture.* 57 (2017)  
393 246–251. <https://doi.org/10.1016/j.gaitpost.2017.06.015>.
- 394 [12] J. Huddleston, A. Alaiti, D. Goldvasser, D. Scarborough, A. Freiberg, H. Rubash, H.  
395 Malchau, W. Harris, D. Krebs, Ambulatory measurement of knee motion and physical  
396 activity: Preliminary evaluation of a smart activity monitor, *J. Neuroeng. Rehabil.* 3

- 397 (2006) 1–10. <https://doi.org/10.1186/1743-0003-3-21>.
- 398 [13] P.Y. de Müllenheim, S. Chaudru, G. Mahé, J. Prioux, A. Le Faucheur, Clinical Interest  
399 of Ambulatory Assessment of Physical Activity and Walking Capacity in Peripheral  
400 Artery Disease, *Scand. J. Med. Sci. Sport.* 26 (2016) 716–730.  
401 <https://doi.org/10.1111/sms.12512>.
- 402 [14] M. Fusca, F. Negrini, P. Perego, L. Magoni, F. Molteni, G. Andreoni, Validation of a  
403 wearable IMU system for gait analysis: Protocol and application to a new system, *Appl.*  
404 *Sci.* 8 (2018) 1–16. <https://doi.org/10.3390/app8071167>.
- 405 [15] K. Tanimoto, M. Takahashi, K. Tokuda, T. Sawada, M. Anan, Lower limb kinematics  
406 during the swing phase in patients with knee osteoarthritis measured using an inertial  
407 sensor, *Gait Posture.* 57 (2017) 236–240. <https://doi.org/10.1016/j.gaitpost.2017.06.017>.
- 408 [16] I. Poitras, F. Dupuis, M. Biemann, A. Campeau-Lecours, C. Mercier, L.J. Bouyer, J.S.  
409 Roy, Validity and reliability of wearable sensors for joint angle estimation: A systematic  
410 review, *Sensors (Switzerland).* 19 (2019) 1–17. <https://doi.org/10.3390/s19071555>.
- 411 [17] H. Dejnabadi, B.M. Jolles, E. Casanova, P. Fua, K. Aminian, Estimation and  
412 visualization of sagittal kinematics of lower limbs orientation using body-fixed sensors,  
413 *IEEE Trans. Biomed. Eng.* 53 (2006) 1385–1393.  
414 <https://doi.org/10.1109/TBME.2006.873678>.
- 415 [18] R. Antonello, K. Ito, R. Oboe, Acceleration Measurement Drift Rejection in Motion  
416 Control Systems by Augmented-State Kinematic Kalman Filter, *IEEE Trans. Ind.*  
417 *Electron.* 63 (2016) 1953–1961. <https://doi.org/10.1109/TIE.2015.2512224>.
- 418 [19] S. Šlajpah, R. Kamnik, M. Munih, Kinematics based sensory fusion for wearable motion  
419 assessment in human walking, *Comput. Methods Programs Biomed.* 116 (2014) 131–  
420 144. <https://doi.org/10.1016/j.cmpb.2013.11.012>.
- 421 [20] R.G. Valenti, I. Dryanovski, J. Xiao, Keeping a good attitude: A quaternion-based  
422 orientation filter for IMUs and MARGs, *Sensors (Switzerland).* 15 (2015) 19302–19330.  
423 <https://doi.org/10.3390/s150819302>.
- 424 [21] M. Nazarahari, A. Noamani, N. Ahmadian, H. Rouhani, Sensor-to-body calibration  
425 procedure for clinical motion analysis of lower limb using magnetic and inertial  
426 measurement units, *J. Biomech.* 85 (2019) 224–229.  
427 <https://doi.org/10.1016/j.jbiomech.2019.01.027>.
- 428 [22] R. Sers, S. Forrester, E. Moss, S. Ward, J. Ma, M. Zecca, Validity of the Perception  
429 Neuron inertial motion capture system for upper body motion analysis, *Measurement.*  
430 149 (2019) 107024. <https://doi.org/10.1016/j.measurement.2019.107024>.
- 431 [23] U. Lindemann, Spatiotemporal gait analysis of older persons in clinical practice and  
432 research: Which parameters are relevant?, *Z. Gerontol. Geriatr.* 53 (2020) 171–178.  
433 <https://doi.org/10.1007/s00391-019-01520-8>.
- 434 [24] J.P. Stellmann, A. Neuhaus, N. Götze, S. Briken, C. Lederer, M. Schimpl, C. Heesen, M.  
435 Daumer, Ecological validity of walking capacity tests in multiple sclerosis, *PLoS One.*  
436 10 (2015) 1–11. <https://doi.org/10.1371/journal.pone.0123822>.
- 437 [25] B.J. McFadyen, M.É. Gagné, I. Cossette, M.C. Ouellet, Using dual task walking as an  
438 aid to assess executive dysfunction ecologically in neurological populations: A narrative  
439 review, *Neuropsychol. Rehabil.* 27 (2017) 722–743.

- 440 <https://doi.org/10.1080/09602011.2015.1100125>.
- 441 [26] J. Clément, R. Dumas, N. Hagemeister, J.A. de Guise, Soft tissue artifact compensation  
442 in knee kinematics by multi-body optimization: Performance of subject-specific knee  
443 joint models, *J. Biomech.* 48 (2015) 3796–3802.  
444 <https://doi.org/10.1016/j.jbiomech.2015.09.040>.
- 445 [27] A. Leardini, G. Lullini, S. Giannini, L. Berti, M. Ortolani, P. Caravaggi, Validation of  
446 the angular measurements of a new inertial-measurement-unit based rehabilitation  
447 system: Comparison with state-of-the-art gait analysis, *J. Neuroeng. Rehabil.* 11 (2014)  
448 1–7. <https://doi.org/10.1186/1743-0003-11-136>.
- 449 [28] A. Peters, B. Galna, M. Sangeux, M. Morris, R. Baker, Quantification of soft tissue  
450 artifact in lower limb human motion analysis: A systematic review, *Gait Posture.* 31  
451 (2010) 1–8. <https://doi.org/10.1016/j.gaitpost.2009.09.004>.
- 452 [29] M.A. Lafortune, P.R. Cavanagh, H.J. Sommer, A. Kalenak, Three-dimensional  
453 kinematics of the human knee during walking, *J. Biomech.* 25 (1992) 347–357.  
454 [https://doi.org/10.1016/0021-9290\(92\)90254-X](https://doi.org/10.1016/0021-9290(92)90254-X).
- 455 [30] D.L. Benoit, M. Damsgaard, M.S. Andersen, Surface marker cluster translation, rotation,  
456 scaling and deformation: Their contribution to soft tissue artefact and impact on knee  
457 joint kinematics, *J. Biomech.* 48 (2015) 2124–2129.  
458 <https://doi.org/10.1016/j.jbiomech.2015.02.050>.
- 459 [31] T.Y. Tsai, T.W. Lu, M.Y. Kuo, H.C. Hsu, Quantification of three-dimensional  
460 movement of skin markers relative to the underlying bones during functional activities,  
461 *Biomed. Eng. - Appl. Basis Commun.* 21 (2009) 223–232.  
462 <https://doi.org/10.4015/S1016237209001283>.
- 463 [32] P. Imbert, C. Belvedere, A. Leardini, Knee laxity modifications after ACL rupture and  
464 surgical intra - and extra - articular reconstructions : intra - operative measures in  
465 reconstructed and healthy knees, *Knee Surgery, Sport. Traumatol. Arthrosc.* 25 (2017)  
466 2725–2735. <https://doi.org/10.1007/s00167-015-3653-1>.
- 467 [33] A. Grassi, C. Signorelli, G.A. Lucidi, F. Raggi, L. Macchiarola, T. Roberti Di Sarsina,  
468 G.M.M. Muccioli, G. Filardo, S. Zaffagnini, ACL reconstruction with lateral plasty  
469 reduces translational and rotatory laxity compared to anatomical single bundle and non-  
470 anatomical double bundle surgery: An in vivo kinematic evaluation with navigation  
471 system, *Clin. Biomech.* 69 (2019) 1–8.  
472 <https://doi.org/10.1016/j.clinbiomech.2019.06.012>.
- 473 [34] P.Z. Feczko, B.G. Pijls, M.J. Van Steijn, L.W. Van Rhijn, J.J. Arts, P.J. Emans, Tibial  
474 component rotation in total knee arthroplasty, *BMC Musculoskelet. Disord.* (2016) 1–6.  
475 <https://doi.org/10.1186/s12891-016-0940-z>.
- 476 [35] D.K. Bae, S.J. Song, Computer Assisted Navigation in Knee Arthroplasty, *Clin. Orthop.*  
477 *Surg.* 3 (2011) 259–267. <https://doi.org/10.4055/cios.2011.3.4.259>.
- 478 [36] A. Nakamae, M. Ishikawa, T. Nakasa, Y. Ikuta, M. Ochi, N. Adachi, Evaluation of the  
479 intraoperative kinematics during double-bundle anterior cruciate ligament reconstruction  
480 using a navigation system, *Asia-Pacific J. Sport. Med. Arthrosc. Rehabil. Technol.* 19  
481 (2020) 11–16. <https://doi.org/10.1016/j.asmart.2019.11.002>.
- 482 [37] P.F. Hill, V. Vedi, A. Williams, H. Iwaki, V. Pinskerova, M.A.R. Freeman, Tibiofemoral



- 483 movement 2: The loaded and unloaded living knee studied by MRI, *J. Bone Jt. Surg. -*  
484 *Ser. B.* 82 (2000) 1196–1198. <https://doi.org/10.1302/0301-620X.82B8.10716>.
- 485 [38] M. Worlicek, B. Moser, G. Maderbacher, R. Zentner, F. Zeman, J. Grifka, A. Keshmiri,  
486 The influence of varus and valgus deviation on patellar kinematics in healthy knees: An  
487 exploratory cadaver study, *Knee.* 24 (2017) 711–717.  
488 <https://doi.org/10.1016/j.knee.2017.04.009>.
- 489 [39] N.A. Mohd Sharif, S.L. Goh, J. Usman, W.K.Z. Wan Safwani, Biomechanical and  
490 functional efficacy of knee sleeves: A literature review, *Phys. Ther. Sport.* 28 (2017) 44–  
491 52. <https://doi.org/10.1016/j.ptsp.2017.05.001>.
- 492 [40] J. Jenny, C. Boeri, F. Picard, F. Leitner, O.I.S. Leitner, Reproducibility of intra-operative  
493 measurement of the mechanical axes of the lower limb during total knee replacement  
494 with a non-image-based navigation system, 9088 (2010).  
495 <https://doi.org/10.3109/10929080500095517>.
- 496 [41] A.I. Cuesta-Vargas, A. Galán-Mercant, J.M. Williams, The use of inertial sensors system  
497 for human motion analysis, *Phys. Ther. Rev.* 15 (2010) 462–473.  
498 <https://doi.org/10.1179/1743288X11Y.0000000006>.
- 499 [42] M.E. Kayaalp, A.N. Agres, J. Reichmann, M. Bashkuev, G.N. Duda, R. Becker,  
500 Validation of a Novel Device for the Knee Monitoring of Orthopaedic Patients, (2019)  
501 1–14. <https://doi.org/10.3390/s19235193>.
- 502 [43] W. Teufl, M. Miezal, B. Taetz, M. Frohlich, G. Bleser, Validity of inertial sensor based  
503 3D joint kinematics of static and dynamic sport and physiotherapy specific movements,  
504 *PLoS One.* 14 (2019) 1–18. <https://doi.org/10.1371/journal.pone.0213064>.
- 505 [44] G. Maderbacher, A. Keshmiri, H.R. Springorum, H. Maderbacher, J. Grifka, C. Baier,  
506 Reproducibility of navigation based kinematic analysis of the knee – A cadaveric  
507 investigation, *J. Orthop. Sci.* 24 (2019) 128–135.  
508 <https://doi.org/10.1016/j.jos.2018.08.027>.
- 509 [45] V. Musahl, K.M. Bell, A.G. Tsai, R.S. Costic, R. Allaire, T. Zantop, J.J. Irrgang, F.H.  
510 Fu, Development of a simple device for measurement of rotational knee laxity, *Knee*  
511 *Surgery, Sport. Traumatol. Arthrosc.* 15 (2007) 1009–1012.  
512 <https://doi.org/10.1007/s00167-007-0317-9>.
- 513 [46] Y.S. Cho, S.H. Jang, J.S. Cho, M.J. Kim, H.D. Lee, S.Y. Lee, S.B. Moon, Evaluation of  
514 validity and reliability of inertial measurement unit-based gait analysis systems, *Ann.*  
515 *Rehabil. Med.* 42 (2018) 872–883. <https://doi.org/10.5535/arm.2018.42.6.872>.
- 516 [47] D. Kobsar, S.T. Osis, A. Phinyomark, J.E. Boyd, R. Ferber, Reliability of gait analysis  
517 using wearable sensors in patients with knee osteoarthritis, *J. Biomech.* 49 (2016) 3977–  
518 3982. <https://doi.org/10.1016/j.jbiomech.2016.11.047>.
- 519 [48] K. Lebel, P. Boissy, H. Nguyen, C. Duval, Inertial measurement systems for segments  
520 and joints kinematics assessment: Towards an understanding of the variations in sensors  
521 accuracy, *Biomed. Eng. Online.* 16 (2017) 1–16. <https://doi.org/10.1186/s12938-017-0347-6>.
- 523 [49] J. Favre, R. Aissaoui, B.M. Jolles, J.A. de Guise, K. Aminian, Functional calibration  
524 procedure for 3D knee joint angle description using inertial sensors, *J. Biomech.* 42  
525 (2009) 2330–2335. <https://doi.org/10.1016/j.jbiomech.2009.06.025>.

- 526 [50] J.L. McGinley, R. Baker, R. Wolfe, M.E. Morris, The reliability of three-dimensional  
527 kinematic gait measurements: A systematic review, *Gait Posture*. 29 (2009) 360–369.  
528 <https://doi.org/10.1016/j.gaitpost.2008.09.003>.
- 529 [51] X. Robert-Lachaine, H. Mecheri, C. Larue, A. Plamondon, Effect of local magnetic field  
530 disturbances on inertial measurement units accuracy, *Appl. Ergon.* 63 (2017) 123–132.  
531 <https://doi.org/10.1016/j.apergo.2017.04.011>.
- 532 [52] K.M. Bell, C. Onyeukwu, M.P. McClincy, M. Allen, L. Bechard, A. Mukherjee, R.A.  
533 Hartman, C. Smith, A.D. Lynch, J.J. Irrgang, Verification of a portable motion tracking  
534 system for remote management of physical rehabilitation of the knee, *Sensors*  
535 (Switzerland). 19 (2019). <https://doi.org/10.3390/s19051021>.
- 536 [53] R. Stagni, S. Fantozzi, A. Cappello, A. Leardini, Quantification of soft tissue artefact in  
537 motion analysis by combining 3D fluoroscopy and stereophotogrammetry: A study on  
538 two subjects, *Clin. Biomech.* 20 (2005) 320–329.  
539 <https://doi.org/10.1016/j.clinbiomech.2004.11.012>.
- 540 [54] B.M. Potvin, M.S. Shourijeh, K.B. Smale, D.L. Benoit, A practical solution to reduce  
541 soft tissue artifact error at the knee using adaptive kinematic constraints, *J. Biomech.* 62  
542 (2017) 124–131. <https://doi.org/10.1016/j.jbiomech.2017.02.006>.
- 543 [55] P. Moewis, H. Boeth, M.O. Heller, C. Yntema, T. Jung, R. Doyscher, R.M. Ehrig, Y.  
544 Zhong, W.R. Taylor, Towards understanding knee joint laxity: Errors in non-invasive  
545 assessment of joint rotation can be corrected, *Med. Eng. Phys.* 36 (2014) 889–895.  
546 <https://doi.org/10.1016/j.medengphy.2014.03.017>.
- 547 [56] C.C. Lin, T.W. Lu, H.L. Lu, M.Y. Kuo, H.C. Hsu, Effects of soft tissue artifacts on  
548 differentiating kinematic differences between natural and replaced knee joints during  
549 functional activity, *Gait Posture*. 46 (2016) 154–160.  
550 <https://doi.org/10.1016/j.gaitpost.2016.03.006>.
- 551 [57] G. Cooper, I. Sheret, L. McMillian, K. Siliverdis, N. Sha, D. Hodgins, L. Kenney, D.  
552 Howard, Inertial sensor-based knee flexion/extension angle estimation, *J. Biomech.* 42  
553 (2009) 2678–2685. <https://doi.org/10.1016/j.jbiomech.2009.08.004>.
- 554 [58] X. Robert-Lachaine, G. Parent, A. Fuentes, N. Hagemeister, R. Aissaoui, Inertial motion  
555 capture validation of 3D knee kinematics at various gait speed on the treadmill with a  
556 double-pose calibration, *Gait Posture*. 77 (2020) 132–137.  
557 <https://doi.org/10.1016/j.gaitpost.2020.01.029>.
- 558 [59] K. Manal, I. McClay, S. Stanhope, J. Richards, B. Galinat, Comparison of surface  
559 mounted markers and attachment methods in estimating tibial rotations during walking:  
560 an in vivo study, 2000. [https://doi.org/10.1016/S0966-6362\(99\)00042-9](https://doi.org/10.1016/S0966-6362(99)00042-9).
- 561 [60] G. Maderbacher, A. Keshmiri, H.R. Springorum, H. Maderbacher, J. Grifka, C. Baier,  
562 Influence of Component Rotation in Total Knee Arthroplasty on Tibiofemoral  
563 Kinematics—A Cadaveric Investigation, *J. Arthroplasty*. 32 (2017) 2869–2877.  
564 <https://doi.org/10.1016/j.arth.2017.03.055>.
- 565 [61] O. Schectman, *Methods of Clinical Epidemiology*, *Methods Clin. Epidemiol.* (2013) 33–  
566 49. <https://doi.org/10.1007/978-3-642-37131-8>.
- 567 [62] P.Z. Du, K.L. Markolf, D. V Boguszewski, K.T. Yamaguchi, C.J. Lama, D.R. Mcallister,  
568 K.J. Jones, Effects of Proud Large Osteochondral Plugs on Contact Forces and Knee

569 Kinematics A Robotic Study, (2018) 1–6. <https://doi.org/10.1177/0363546518770415>.

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571