Isokinetics and Exercise Science 24 (2016) 301–311
DOI 10.3233/IES-160630
IOS Press

Minimal fixation suffices for supine isokinetic knee extension: A kinetic and 3D kinematic analysis

Tobias Alt[a,*], Michel Richert[a], Yannick M. Schwarz[a], Axel J. Knicker[a,b] and Heiko K. Strüder[a]
[a]*Institute of Movement and Neuroscience, German Sport University, Cologne, Germany*
[b]*SPRINZ Sport Performance Research Institute of New Zealand, Auckland University of Technology, New Zealand*

Abstract.
BACKGROUND: Isokinetic tests are used to measure muscular performance, especially strength. A proper axis alignment ensures high measuring accuracy.
OBJECTIVE: The effects of fixation (minimal vs. maximal), contraction mode (concentric vs. eccentric) and angular velocity (30 vs. 150°/s) on the kinetics and 3D kinematics of supine knee extensions need further investigation.
METHODS: Eighteen healthy male participants (22.1 y, 1.83 m, 76.0 kg) performed maximal unilateral contractions with minimal (hand grips only) and maximal (grips, knee, hip and trunk straps) fixation.
RESULTS: Peak moments (+5%) and contractional work (+4%) significantly increased at minimal fixation. Maximal fixation improved sagittal axis alignment in terms of the trajectory length of the lateral femoral epicondyle (−34%) and the mean distance to trajectory centre (−19%). Both kinematic parameters showed highly significant interactions of fixation, contraction mode and angular velocity ($p < 0.01$). Initial axis alignment in relaxed muscular state caused an antero-cranial shift (0.8 and 2.4 cm) of the lateral femoral epicondyle as well as mean roll and yaw angle tilts of each 2.3° each.
CONCLUSIONS: For supine isokinetic knee extensions, hand grips suffice as fixation to obtain accurate kinematic and kinetic results. If fixation is tight, the force output will decrease. To minimise misalignment, lining up should be executed when muscles are contracting isometrically.

Keywords: Axis alignment, stabilisation, peak moment, transepicondylar axis, roll angle, yaw angle

1. Introduction

Knee muscular capacity plays an important role in many sports regarding performance improvement and injury prevention. It is often assessed by isokinetic strength tests assuming that the rotation centre of the knee joint remains fixed. However, knee joint mechanics is not as simple because its sagittal movement is not perfectly aligned with a fixed frontal axis [1,2]. Due to the combined rotation and translation of the femur on the tibial plateau during knee extension, the actual pathway of the knee joint centre appears to describe some kind of an involute [3,4]. This leads to some error in isokinetic tests of knee muscles [5,6]. Nonetheless, a proper axis alignment is necessary to obtain reliable and valid results [7,8] as a severe misalignment impairs the measured moment and contractional work [9–12]. The transepicondylar axis was identified as an easy palpatory method to represent the knee flexion-extension axis by bony landmarks [1].

Another important feature of isokinetic test procedures is that of subject's fixation [7]. There is a controversial discussion concerning the effect fixation has on isokinetic test findings. Most studies revealed that fixation increased force production [13–17], while some

---

[*] Corresponding author: Tobias Alt, Institute of Movement and Neuroscience, German Sport University, Am Sportpark Müngersdorf 6, 50933 Cologne, North Rhine-Westphalia, Germany. Tel.: +49 221 4982 3322; Fax: +49 221 4973454; E-mail: t.alt@dshs-koeln.de.

ISSN 0959-3020/16/$35.00

failed to confirm this [18]. However, all of these studies were conducted in a seated position with a hip flexion of 70–90°. In order to simulate fibre lengths that occur during the mid stance of running and sprinting a smaller hip flexion angle (0–20°) is advisable for practice-oriented strength diagnosis of the thigh muscles [19,20].

Surprisingly, the effect of fixation on the three-dimensional axis deviation between the knee joint ‘axis’ and dynamometer axis during isokinetic knee extensions has not been investigated yet. Thus, the hypotheses of the present study were:

1) Peak moments and contractional work increase when maximal fixation is applied.
2) Maximal fixation improves the alignment between transepicondylar and dynamometer axes.
3) The interaction of fixation with angular velocity and/or contraction mode has no further influence on the derived kinetic and kinematic parameters.

Knowledge regarding these kinetic and kinematic interdependencies is important for scientists and clinicians conducting isokinetic strength tests and/or rehabilitation training. It may also assist in ensuring functional loading on the involved biological tissues.

2. Methods

2.1. Subjects

Eighteen healthy male participants (mean ± SD, age: 22.1 ± 2.0 years, height: 1.83 ± 0.05 m, mass: 76.0 ± 4.9 kg) gave their written informed consent to participate in this study. They were familiarized with isokinetic strength tests and lower extremity resistance training. All participants were free of injuries, pain or other limitations that might have inhibited maximum force exertion. The local ethics commission confirmed that the requirements of the Declaration of Helsinki were fulfilled.

2.2. Procedures

All subjects performed two sessions (familiarisation and testing) separated by 72–96 h. The sessions followed identical procedures and were performed at the same time of day (± 1 h) and by the same examiner. After weighing the participants individually warmed up (jogging, dynamic stretching) for ten minutes. This general warm-up was followed by the subject’s positioning on the active isokinetic dynamometer (IsoMed 2000, D&R Ferstl GmbH, Hemau, Germany). To reduce acceleration errors, the participants took off their shoes. The participants were asked to lie in a supine position with a 20° flexed hip. At 90° knee flexion and in a relaxed muscular state, the mechanical axis of the dynamometer was aligned with the transepicondylar axis of the subject’s left knee by the aid of a laser pointer. Therefore, the dynamometer was horizontally rotated and accordingly inclined. The lateral and medial femoral epicondyles (Fig. 1, point 1 and 2) were palpated and marked with retro-reflective spheres (Ø 8 mm), respectively. A third spherical marker was fixed by tape onto the lever arm of the dynamometer (Fig. 1, point 3). The individual settings of each participant were saved for accurate repositioning by the manufacturer’s computer software IsoMed analyze V.2.0. Afterwards, a three-dimensional calibration frame (40 × 40 × 40 cm) with twelve retro-reflective markers (Ø 10 mm) was mounted on the rotation axis of the isokinetic dynamometer. A static calibration was conducted by two cameras (Basler A602fc-2, Basler AG, Ahrensburg, Germany) recording the transverse (from ahead) and frontal plane (from above). Two headlights (Bar Fly 200, Kino Flo® Lightning Systems, Burbank, CA, USA) supported the visibility of the markers. The three movement planes were defined as shown in Fig. 2.

After removing the calibration frame, a double shin pad for unilateral knee extension was attached to the motor-driven axis. The distal part of the double shin pad was fastened by straps approximately 2–3 cm proximal to the lateral malleolus. The integrated software executed a static gravity correction in horizontal lever arm position during relaxed muscular state. In sequence, each participant was fixed both minimally ($\mathrm{Fix}_{\mathrm{min}}$) (hand grips only) and maximally ($\mathrm{Fix}_{\mathrm{max}}$) (grips, knee, hip and trunk strap) (Fig. 1). The order of the fixation condition was random. The knee fixation was fastened at 200 N measured by a hand scale (First Austria, TIMETRON., Vienna, Austria) to prevent any unwanted evasive movements. Following each fixation condition, the participants performed 15 submaximal (∼50%) concentric and eccentric knee extensions at 60°/s. For both contraction conditions, a small isometric pre-activation threshold of 20 Nm was used [21]. During the following test sets, concentric (con) and eccentric (ecc) knee extensions were conducted discretely at 30°/s and 150°/s with maximum effort. According to general recommendations, slow velocities were tested prior to fast ones and discrete movements in a single direction (uni-directional) were conducted [22,23]. Within one fixation condition the

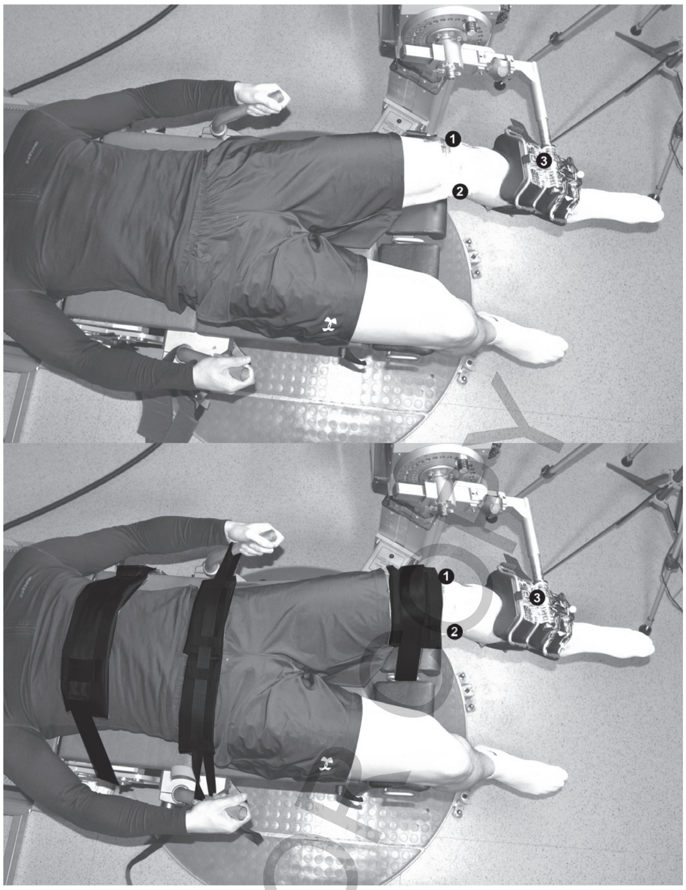

Fig. 1. Minimal (top) and maximal (bottom) fixation condition during supine isokinetic knee extension. The three retro-reflective markers represented the lateral (point 1) and medial (point 2) femoral epicondyle as well as the motion of the lever arm (point 3).

sequence remained the same: 30con, 30ecc, 150con, 150ecc. The range of motion was set at 90° starting at full knee extension (0°). A very quick acceleration and a hard deceleration ensured the largest possible isokinetic range of motion. Each set consisted of five repetitions (two practice and three with maximum effort). The last three repetitions were used for further analysis. The inter-set rest interval lasted one minute [24]. During the tests, laboratory lighting was turned off.

Kinetic raw data were recorded at a sampling rate of 200 Hz (IsoMed analyze V.2.0, D&R Ferstl GmbH, Hemau, Germany) and high-speed videos with 100 Hz (Basler A602fc-2, Basler AG, Ahrensburg, Germany). Kinematic data were captured and processed in Vicon Motus (V9.2, VICON TM, Oxford, UK). The vertical trajectory of the lever arm marker (Fig. 1, point 3) served to determine the start and end of the respective movement. Roll (α) and yaw (β) angles were defined as shifts – related to the dynamometer axis (y-axis) – of the transepicondylar axis in the transverse and frontal plane (Fig. 2). Positive directions represented relative hip internal rotation (anterior motion of the lateral femoral epicondyle in relation to the medial one) and adduction (caudal motion of the lateral femoral epicondyle in relation to the medial one). The sagittal trajectory lines of the lateral femoral epicondyle were plotted for each condition (Fig. 3) and their lengths were computed to obtain a quantitative measure of the combined rotational and translational motion of the knee axis (sagittal trajectory length = stl). The trajectory centre was calculated by arithmetic means in antero-posterior (trajectory centre shift along x-axis = tcsx) and cranio-caudal direction (trajectory centre shift along z-axis = tcsz). The sagittal distance to the trajectory centre expressed the mean two-dimensional displacement of the transepicondylar track to its respective centre and thus the spatial expansion of the knee joint axis (sagittal distance to trajectory centre = sdtc).

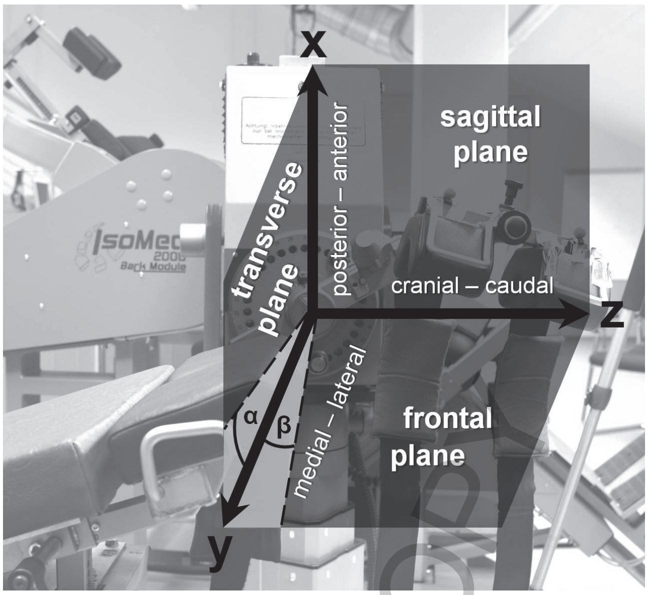

Fig. 2. Functional movement planes of the calibrated volume (40 × 40 × 40 cm). Roll (α = rotation around z-axis) and yaw (β = rotation around x-axis) angles quantified the shifts of the transepicondylar axis in the transverse and frontal plane in relation to the dynamometer axis (y-axis).

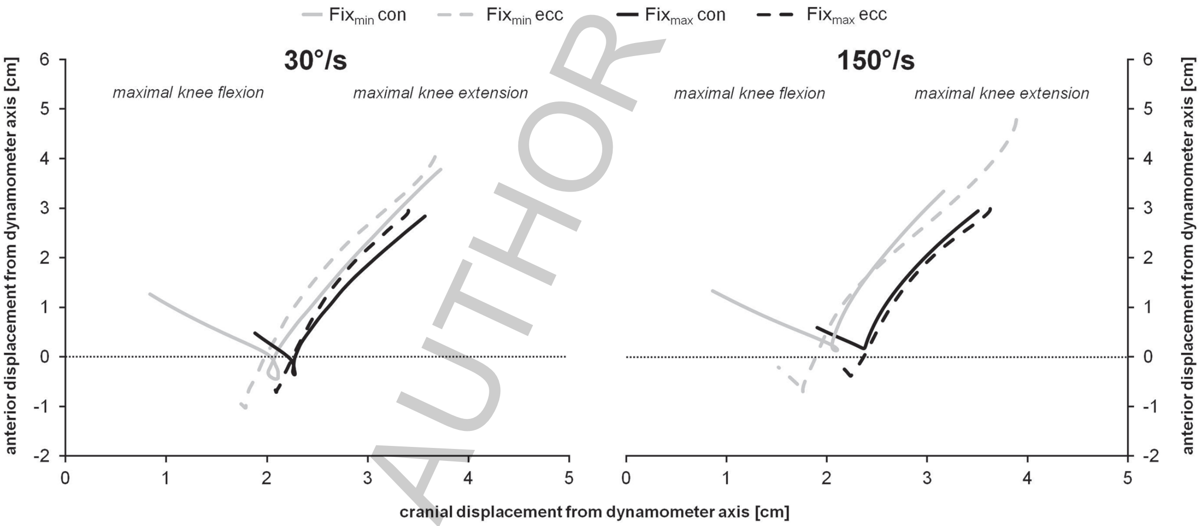

Fig. 3. Mean antero-cranial displacement of the lateral femoral epicondyle in relation to the dynamometer axis (coordinate origin) obtained from concentric (solid lines) and eccentric (dashed lines) knee extensions at 30°/s (left) and 150°/s (right) with minimal ($\mathrm{Fix_{min}}$ = grey lines) and maximal ($\mathrm{Fix_{max}}$ = black lines) subjects' fixation. The temporal course of shortening contractions is from left (maximal knee flexion) to right (maximal knee extension) and vice versa for lengthening contractions.

Kinetic raw data were stored as ASCII files. By the aid of a custom software written in C++, a 5^{th} order Butterworth low-pass filter with a cut-off frequency of 6 Hz was applied and the isokinetic range of motion was identified. Afterwards, the relevant test parameters from the obtained moment-angle curves were computed: highest gravity-corrected peak moments (PM), angles of peak moment (APM) and contractional work (CW).

2.3. Statistical analyses

Kolmogorov-Smirnov ($p \leqslant 0.05$) and Levene's tests ($p \leqslant 0.10$) proved normal distribution and variance homogeneity. A three-way ANOVA with repeated measures ($2 \times 2 \times 2$) examined significant effects of fixation ($\mathrm{Fix}_{\min}$ and $\mathrm{Fix}_{\max}$), contraction mode (con and ecc) and angular velocity (30 and 150°/s) on kinematic (sagittal trajectory length, shift of trajectory centre in antero-posterior and cranio-caudal direction, sagittal distance to trajectory centre, roll and yaw angle) and kinetic parameters (PM, APM, CW). Via Bonferroni post hoc tests ($p \leqslant 0.05$) actual p-values were calculated. The partial eta-squared (partial η^2) served to report the effect size and thus the meaningfulness of the present results. With respect to Cohen's rule of thumb [25], a small, medium and large effect size was reached at 0.02, 0.13 and 0.26, respectively. All statistical tests were executed with SPSS (V22.0, SPSS Inc., Chicago, Illinois, USA).

3. Results

Table 1 lists all kinetic and kinematic results obtained from concentric and eccentric supine knee extensions with minimal and maximal subject's fixation. For a better visibility, significant effects are highlighted by grey accentuation.

3.1. Kinetic results

Maximal fixation lead to considerable reductions of peak moment (PM) (-2% to -8%, $p = 0.020$, $\eta^2 = 0.280$) and contractional work (CW) (-1 to -10%, $p = 0.012$, $\eta^2 = 0.318$) throughout all contraction conditions (Table 1). These fixation effects were large. Angles of peak moment (APM) remained unaffected ($p = 0.509$) by fixation. Furthermore, the contraction mode and the angular velocity influenced PM and CW. APM showed a dependence on velocity as well. In addition, a strong interaction of contraction mode and angular velocity became apparent for PM ($p = 0.000$, $\eta^2 = 0.628$) (Table 1).

3.2. Kinematic results

Figure 3 illustrates the antero-cranial displacement of the lateral femoral epicondyle in relation to the dynamometer axis (coordinate origin). Initial axis alignment in relaxed muscular state caused an antero-cranial shift (0.8 and 2.4 cm) during maximal contractions. Maximal fixation lead to an increase of cranial trajectory centre shift ($p = 0.005$, $\eta^2 = 0.375$) (Table 1). The anterior displacement of the trajectory centre was independent of fixation ($p = 0.854$) and reached minimal values when eccentric movements at slow angular velocities were performed ($p = 0.008$, $\eta^2 = 0.351$). The interaction of fixation, contraction mode and angular velocity on sagittal trajectory length revealed a highly significant effect with the smallest spatial expansion of the transepicondylar axis occurring when maximal fixation was applied during fast eccentric contractions ($p = 0.000$, $\eta^2 = 0.522$). The same was true for the sagittal distance to trajectory centre at fast concentric contractions with maximal fixation ($p = 0.008$, $\eta^2 = 0.349$) (Table 1).

Figure 4 shows the roll (top) and yaw angle (bottom) histories of the transepicondylar axis in relation to the dynamometer axis (zero line). In the course of the 90° knee extensions, there was an average misalignment of 2.3° each towards external hip rotation and hip abduction. Roll angles were significantly reduced when participants performed concentric contractions with minimal fixation ($p = 0.027$, $\eta^2 = 0.255$). A similar interaction effect of fixation and contraction mode emerged for yaw angles. However, it failed to reach statistical significance, but displayed a medium effect of minimal fixation and concentric movements ($p = 0.089$, $\eta^2 = 0.161$). The same was applicable to the pure fixation effect on the yaw angle ($p = 0.055$, $\eta^2 = 0.200$). Furthermore, transverse and frontal plane kinematics were influenced by the angular velocity so far as roll angles increased at 150°/s ($p = 0.000$, $\eta^2 = 0.551$), whereas yaw angles generally diminished at fast contraction speed ($p = 0.027$, $\eta^2 = 0.255$).

4. Discussion

The aims of the present study were to examine the effect of subjects' fixation on kinetic data and on the three-dimensional axis alignment during supine knee extensions as well as to identify the additional influence of contraction mode and angular velocity on the aforementioned kinematic and kinetic characteristics. The following discussion is arranged according to the three hypotheses.

4.1. Peak moments and contractional work increase when maximal fixation is applied

Peak moments and contractional work were consistently reduced throughout all contraction conditions when participants were maximally fixed (Table 1). This finding is in opposition to the currently held opinion that fixation increases force output [13–17]. However, two major rationales may be associated with this,

Table 1

Effects of subjects' fixation (fix), contraction mode (contrac) and angular velocity (vel) on kinetic and kinematic parameters obtained from supine isokinetic knee extensions

	150ecc	30ecc	30con	150con	fixation	contraction	velocity	fix*contrac	fix*vel	contrac*vel	fix*contrac*vel
Kinetics											
PM_Fix$_{\min}$ [Nm]	255.3 ± 50.5	280.4 ± 64.2	224.3 ± 40.0	180.2 ± 20.2	$p = 0.020^*$	$p = 0.000^{**}$	$p = 0.000^{**}$	$p = 0.429$	$p = 0.562$	$p = 0.000^{**}$	$p = 0.495$
PM_Fix$_{\max}$ [Nm]	241.4 ± 68.8	274.5 ± 85.4	211.6 ± 41.3	166.3 ± 21.1	$\eta^2 = 0.280$	$\eta^2 = 0.676$	$\eta^2 = 0.530$	$\eta^2 = 0.037$	$\eta^2 = 0.020$	$\eta^2 = 0.628$	$\eta^2 = 0.028$
APM_Fix$_{\min}$ [°]	61.5 ± 6.4	68.5 ± 7.4	68.0 ± 7.6	61.9 ± 8.3	$p = 0.509$	$p = 0.690$	$p = 0.000^{**}$	$p = 0.594$	$p = 0.103$	$p = 0.236$	$p = 0.570$
APM_Fix$_{\max}$ [°]	59.9 ± 4.6	67.9 ± 6.9	67.2 ± 7.0	61.7 ± 8.1	$\eta^2 = 0.026$	$\eta^2 = 0.010$	$\eta^2 = 0.615$	$\eta^2 = 0.017$	$\eta^2 = 0.149$	$\eta^2 = 0.081$	$\eta^2 = 0.019$
CW_Fix$_{\min}$ [J]	252.1 ± 46.4	280.0 ± 65.0	214.4 ± 42.1	196.0 ± 21.4	$p = 0.012^*$	$p = 0.000^{**}$	$p = 0.041^*$	$p = 0.248$	$p = 0.695$	$p = 0.077$	$p = 0.242$
CW_Fix$_{\max}$ [J]	242.5 ± 65.0	277.1 ± 79.0	204.9 ± 45.3	178.8 ± 24.3	$\eta^2 = 0.318$	$\eta^2 = 0.743$	$\eta^2 = 0.224$	$\eta^2 = 0.078$	$\eta^2 = 0.009$	$\eta^2 = 0.172$	$\eta^2 = 0.080$
Kinematics											
tcsx_Fix$_{\min}$ [cm]	0.8 ± 0.9	0.4 ± 0.9	0.7 ± 0.8	1.2 ± 0.8	$p = 0.854$	$p = 0.000^{**}$	$p = 0.000^{**}$	$p = 0.071$	$p = 0.090$	$p = 0.008^{**}$	$p = 0.734$
tcsx_Fix$_{\max}$ [cm]	0.7 ± 0.9	0.5 ± 0.9	0.7 ± 0.8	1.1 ± 0.8	$\eta^2 = 0.002$	$\eta^2 = 0.560$	$\eta^2 = 0.854$	$\eta^2 = 0.180$	$\eta^2 = 0.160$	$\eta^2 = 0.351$	$\eta^2 = 0.007$
tcsz_Fix$_{\min}$ [cm]	2.2 ± 1.0	2.2 ± 0.8	2.3 ± 0.9	2.2 ± 1.0	$p = 0.005^{**}$	$p = 0.368$	$p = 0.308$	$p = 0.544$	$p = 0.056$	$p = 0.060$	$p = 0.944$
tcsz_Fix$_{\max}$ [cm]	2.6 ± 0.9	2.4 ± 0.9	2.6 ± 0.8	2.6 ± 0.8	$\eta^2 = 0.375$	$\eta^2 = 0.061$	$\eta^2 = 0.048$	$\eta^2 = 0.022$	$\eta^2 = 0.198$	$\eta^2 = 0.193$	$\eta^2 = 0.000$
stl_Fix$_{\min}$ [cm]	7.3 ± 2.3	6.2 ± 1.3	7.6 ± 1.2	6.2 ± 1.5	$p = 0.000^{**}$	$p = 0.445$	$p = 0.013^*$	$p = 0.970$	$p = 0.032^*$	$p = 0.000^{**}$	$p = 0.000^{**}$
stl_Fix$_{\max}$ [cm]	4.2 ± 0.9	4.6 ± 1.0	5.1 ± 1.3	4.0 ± 0.9	$\eta^2 = 0.805$	$\eta^2 = 0.035$	$\eta^2 = 0.312$	$\eta^2 = 0.000$	$\eta^2 = 0.242$	$\eta^2 = 0.822$	$\eta^2 = 0.522$
sdtc_Fix$_{\min}$ [cm]	1.5 ± 0.3	1.3 ± 0.2	1.2 ± 0.2	1.2 ± 0.2	$p = 0.000^{**}$	$p = 0.001^{**}$	$p = 0.071$	$p = 0.113$	$p = 0.002^{**}$	$p = 0.001^{**}$	$p = 0.008^{**}$
sdtc_Fix$_{\max}$ [cm]	1.1 ± 0.2	1.1 ± 0.3	1.0 ± 0.2	1.0 ± 0.2	$\eta^2 = 0.848$	$\eta^2 = 0.464$	$\eta^2 = 0.180$	$\eta^2 = 0.141$	$\eta^2 = 0.426$	$\eta^2 = 0.470$	$\eta^2 = 0.349$
roll_Fix$_{\min}$ [°]	−2.5 ± 3.2	−1.9 ± 4.0	−1.5 ± 3.7	−2.2 ± 3.5	$p = 0.398$	$p = 0.982$	$p = 0.000^{**}$	$p = 0.027^*$	$p = 0.674$	$p = 0.969$	$p = 0.617$
roll_Fix$_{\max}$ [°]	−2.9 ± 3.1	−1.9 ± 3.3	−2.3 ± 3.0	−3.1 ± 3.6	$\eta^2 = 0.042$	$\eta^2 = 0.000$	$\eta^2 = 0.551$	$\eta^2 = 0.255$	$\eta^2 = 0.011$	$\eta^2 = 0.000$	$\eta^2 = 0.015$
yaw_Fix$_{\min}$ [°]	−2.0 ± 3.0	−2.4 ± 3.2	−2.1 ± 3.1	−1.7 ± 3.0	$p = 0.055$	$p = 0.617$	$p = 0.027^*$	$p = 0.089$	$p = 0.951$	$p = 0.702$	$p = 0.816$
yaw_Fix$_{\max}$ [°]	−2.2 ± 3.1	−2.7 ± 3.0	−2.8 ± 3.1	−2.5 ± 2.9	$\eta^2 = 0.200$	$\eta^2 = 0.015$	$\eta^2 = 0.255$	$\eta^2 = 0.161$	$\eta^2 = 0.000$	$\eta^2 = 0.009$	$\eta^2 = 0.003$

Significant ($p \leqslant 0.05$) and highly significant ($p \leqslant 0.01$) differences are marked with * and ** (see grey boxes), respectively, partial eta squared (η^2) indicate effect sizes, PM = peak moment, APM = angle of peak moment, CW = contractional work, Fix$_{\min}$ = minimal fixation, Fix$_{\max}$ = maximal fixation, stl = sagittal trajectory length; tcsx = trajectory centre shift along x-axis; tcsz = trajectory centre shift along z-axis, sdtc = sagittal distance to trajectory centre.

seemingly surprising result. First, the maximal fixation – especially the knee strap which was fastened with 200 N – was too severe and resulted in discomfort and elevated muscle tension in the inter-set rest. Second, maximal fixation reduced the force-potentiating synergistic muscle activity e.g. of the hip flexors. Nevertheless, angle of peak moments remained unaffected by fixation so that the shape of the moment-angle relations was unchanged.

It may not matter which of these two factors was dominant or whether this significant effect was a result of both. However, this study presents the first empirical evidence that fixation during isokinetic strength tests does not strictly follow the advice: ‘the more fixation I apply, the more peak moment and contraction work I will get’. Hanten and Ramberg [18] suggested that peak moments obtained from concentric and eccentric knee extensions were unaffected by different fixation procedures. Another study demonstrated that electromyographic findings were not able to account for the increased force output during maximally fixed knee extensions [14]. Instead, the abutment created by the hand, arm and trunk muscles appeared to play a decisive role [14,15]; if the participant is able to create a fixed abutment by his muscles and thus produces an ‘active internal fixation’ to the lounger, the external fixation provided by passive straps may not be an issue of interest. For these reasons, the first hypothesis has to be rejected.

4.2. *Maximal fixation improves the alignment between transepicondylar and dynamometer axis*

There are several studies examining the differences between resultant and measured joints moments as a result of axis misalignment [6,11,12]. However, no study known to us had investigated the effect of fixation on the 3-D axis deviation between the knee joint and the dynamometer axis during isokinetic knee extensions. Whereas the general shape of the sagittal trajectories of the lateral femoral epicondyle remained virtually the same, their spatial expansion was significantly affected by subject’s fixation (Fig. 3). Trajectory lengths (-34%) and the sagittal distance to the trajectory centre (-19%) were considerably reduced when maximal fixation was applied (Table 1). These effects express an improved axis alignment. The eliminated parts of the unfixed trajectories can be classified as unfunctional, evasive movement patterns which occurred when thigh fixation was unfastened (Fig. 3).

As the initial axis alignment in a relaxed muscular state caused a mean antero-cranial shift (0.8 and 2.4 cm) of the lateral femoral epicondyle during maximal contractions, the cranial trajectory centre shift increased significantly with maximal fixation (Table 1). This significantly greater distance to the dynamometer axis might be due to deformations and skin movement caused by the knee strap as well as the expanded range of motion during the minimally fixed shortening contractions at knee flexion (Fig. 3). We expect that if the initial axis alignment had been checked whilst muscles were contracting isometrically, this result would not have emerged. For that reason this supposed feature should be interpreted with appropriate caution. Nevertheless, this outcome points to an important fact that is neither mentioned in any review nor in any empirical isokinetic study. Due to substantial deformations of the muscles and soft parts of the human body, axis alignment substantially deviates from the relaxed muscular state. In this case, mean axis deviation in anterocranial direction (0.8 and 2.4 cm) lay within a range which most likely did not lead to measuring inaccuracies occurring when average axis misalignment exceeds 4 cm [5,8–10]. The frontal and transverse plane kinematics revealed no sole effect of fixation on roll and yaw angles.

In spite of the previously mentioned methodological limitations, the second hypothesis can be confirmed for sagittal plane kinematics, but should be rejected for the frontal and transverse planes.

4.3. *The interaction of fixation with angular velocity and/or contraction mode has no further influence on the kinetic and kinematic parameters*

Kinetic parameters demonstrated no further interaction effects. In accordance to the sole effect of maximal fixation on the sagittal trajectory length and the sagittal distance to trajectory centre, highly significant ($p < 0.01$) and large ($\eta^2 > 0.260$) effect sizes of the interaction between fixation, angular velocity and contraction mode on these two kinematic parameters was apparent (Table 1). Whereas the smallest spatial expansion of the trajectory length took place when maximal fixation was applied during fast eccentric contractions, sagittal distance to trajectory centre was lowest at fast concentric contractions (Fig. 3). This difference provides new insights into the three-dimensional movement patterns of the knee joint during isokinetic exercises and thus needs further investigation. In contrast to sagittal plane kinematics (Fig. 3) and the yaw angle (Fig. 4, bottom), the qualitative analysis of roll angle characteristics unveiled larger fixation-dependent deviations dur-

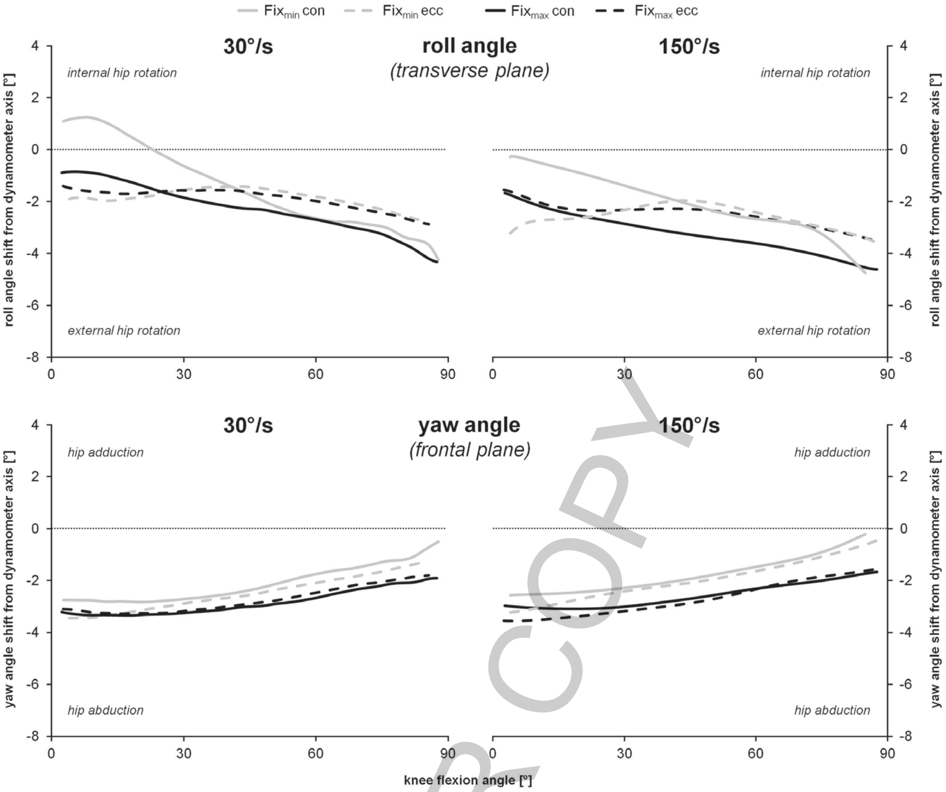

Fig. 4. Mean roll (top) and yaw angle (bottom) characteristics of the transepicondylar axis in relation to the dynamometer axis (zero line) obtained from concentric (solid lines) and eccentric (dashed lines) knee extensions at 30°/s (left) and 150°/s (right) with minimal ($\mathrm{Fix_{min}}$ = grey lines) and maximal ($\mathrm{Fix_{max}}$ = black lines) subjects' fixation. Positive tilts indicate internal hip rotation (roll angle) and hip adduction (yaw angle).

ing concentric contractions (Fig. 4, top). Yet following the aforementioned explanation, this statistically significant advantage of minimal fixation and concentric exercise might be caused by skin movement initiated by fastening of the knee strap as well (Table 1). A similar – not yet significant – but identifiable difference between the two fixation conditions can be recognised for the yaw angle histories (Fig. 4, bottom).

In the course of the concentric and eccentric knee extensions, an average misalignment of the roll and yaw angles of 2.3° each occurred towards external hip rotation and hip abduction (Fig. 4). Similar to the sagittal trajectories of the knee joint axis, it is physiologically impossible that the dynamometer axis perfectly matches the three-dimensional knee pathway. The rationale for this fact is that the roll and yaw angle possessed a 'natural' average motion span of 4.1° and 1.9° for concentric as well as 1.6° and 2.1° for eccentric contractions, respectively (Fig. 4). During knee extensions, the roll angle increased towards external hip rotation, whereas the yaw angle diminished towards hip adduction. This simultaneously emerging three-dimensional movement pattern is a further, not yet illustrated phenomenon (Fig. 4) which might be inherent in the complex mechanics during isokinetic knee exercises [1–4].

Thus, the third hypothesis holds for the kinetic (PM, APM and CW) and some of the kinematic outcomes (anterior and cranial trajectory centre shift, yaw angle). However, it is invalid for some other kinematic parameters (roll angle with constraint, sagittal trajectory length and sagittal distance to trajectory centre).

4.4. Synopsis

Table 2 lists the advantages of minimal and maximal subjects' fixation as well as the unaffected parameters. As mentioned in the two preceding paragraphs some of the observed differences were caused by inappropriate initial misalignment which could likely be attributed to a certain extent to each examiner. The average deviations – an antero-cranial shift of 0.8 and 2.4 cm as well as mean roll and yaw angle tilts of 2.3° each – seemed to be acceptable with respect to the physiolog-

Table 2
Advantages of minimal and maximal subjects' fixation as well as unaffected parameters concerning kinematic and kinetic parameters obtained from supine isokinetic knee extensions. Parameters written in italics indicate effects of fixation that might be due to initial misalignment, deformations and skin movement

Advantages of minimal fixation	Unaffected	Advantages of maximal fixation
+5% peak moment	angle of peak moment	−34% sagittal trajectory length of lateral femoral epicondyle
+4% contractional work	anterior shift of trajectory centre in relation to external rotation axis	−19% mean sagittal distance of trajectory line to its centre
−13% cranial shift of trajectory centre in relation to external rotation axis	roll angle *(trend in favour of minimal fixation)*	
	yaw angle *(trend in favour of minimal fixation)*	

ically inherent unconformity of the human knee joint compared to a perfect hinge joint [1–5]. To minimise misalignment, we recommend initial lining up to be executed or at least verified when muscles are contracting isometrically. If fixation is too severe, force output will significantly decrease, both for peak values and throughout the whole range of motion. In contrast, maximal fixation considerably improved the sagittal axis alignment because the two-dimensional expansion of the transepicondylar trajectory was significantly reduced (Table 1 and Fig. 3). It has to be admitted that the observed differences of 4–5% may be considered negligible when regarding the total measurement error accounting for approximately 12–15% [19]. Nevertheless, the kinetic effects would have been more relevant if the resultant and not the measured moments had been analysed [6].

After reviewing the advantages and disadvantages of maximal fixation, most of the supine isokinetic knee extension tests can be performed with minimal fixation as hand grips provide sufficient 'active internal fixation' to the lounger. It is a time-saving procedure for the examiner and a more comfortable way for the patient/athlete to exert his/her maximum muscular effort [18]. Nevertheless, to ensure a high standardisation, the examiner has to check if the patient/athlete executes unwanted evasive movements which might diminish the measurement accuracy. Therefore, a good instruction as well as a proper and separate familiarisation session is crucial [19,20]. However, if muscular strength is not sufficient to ensure an adequate internal fixation through grip, arm and trunk muscles (e.g. among females), additional external fixation will be indispensable [14,15].

4.5. Limitations

The present study incorporated four major constraints. First, the initial axis alignment in relaxed muscular state lead to an antero-cranial shift of 0.8 and 2.4 cm as well as mean roll and yaw angle tilts of 2.3° each (Table 1). Especially, the soft tissue deformation-induced sagittal displacement of the lateral femoral epicondyle would have been reduced if initial lining had been executed or at least verified in a contracted muscular state.

Second, the knee joint fixation was apparently too severe and resulted in discomfort and elevated muscle tension in the inter-set rest periods. This might have minimised the mechanical output of the participants. That said, the goal was met as any unwanted evasive movements were prevented (Fig. 3).

Third, the tight fastening of the knee strap initiated skin movement which might have lead to additional measurement inaccuracies. These probably became apparent with regard to the yaw angle characteristics as there was a consistent shift towards larger frontal plane misalignment when maximal fixation was applied (Fig. 4 bottom).

Fourth, the knee model used in this study was very simple [1]. The obtained sagittal transepicondylar trajectories corresponded in broad outline to former studies describing the pathway of the knee flexion-extension axis as an antero-caudally opened involute [3,4]. With regard to the presented results according to a previous study [8], the mean trajectories rather looked like antero-caudally opened ticks just suggesting the combined rotation and translation of the femur on the tibial plateau during knee extension (Fig. 3). The observed discrepancies in maximal knee flexion and extension might be due to the fact that these studies used magnetic resonance images and serial X-rays to determine the actual knee joint axis. However, our results – based on a palpatory representation of the transepicondylar axis – may be rated as a good approximation of the imaging techniques which normally serve as the gold standards [1–4]. They also represent the generally accepted and recommended practical application and procedure for knee axis alignment during subjects' positioning on an isokinetic dynamometer [7].

Fifth, the interpretation of measured moments was simplistic. Although in most clinical and diagnostic settings solely measured moments are analysed, the calculation of the resultant moments might have provided more sophisticated results [6].

4.6. *Perspectives*

The presented method might be used for internal validation of every isokinetic test and of each examiner to check their measuring accuracy concerning axis alignment. As soon as the necessary equipment (cameras, headlights, measuring computer) is installed and assembled, it is a fairly easy and quick procedure. In further studies, a proper initial axis alignment with an ultimate check in a contracted muscular state is strongly recommended. A more complex knee joint model with more markers (e.g. technical markers) might reduce measuring inaccuracies caused by skin movement. Furthermore, the kinematics of the hip and trunk can be recorded as well to quantify the evasive movements executed during minimal fixation [8]. For this purpose, more cameras and a larger calibration volume is needed. Most isokinetic knee tests appear to be conducted with a dynamometer alignment which was perpendicular to the sagittal plane [8–10,13–20]. It might be of interest to quantify its three-dimensional kinematic differences compared to an inclined and horizontally-rotated dynamometer head – as it was employed in the present study. Additionally, gender differences need further research. It can be expected that due to lower strength capacities in stabilizing muscles (e.g. hands, arms, trunk), females will have a greater misalignment compared to males when minimal fixation is applied [14,15]. Finally, the same evaluation should be conducted for concentric and eccentric hamstring exercises in prone position. Apart from a high reliability [20], this body position facilitates a higher force generation in comparison with the supine position [26]. It is hypothesised that there might be a much larger knee axis deviation as a reasonable fixation of the thigh, hip and trunk is much more difficult to realise than the knee extensions. Besides, a real abutment in terms of a solid pad (e.g. in the knee hollow) is missing.

5. Conclusions

The presented results provide first empirical insights into the effects of subjects' fixation, contraction mode and angular velocity on the kinetics and 3D kinematics of supine knee extensions. After weighing the advantages and disadvantages of maximal fixation, we suggest that hand grips suffice to obtain accurate kinematic and kinetic results. If fixation is too severe, the extension moment output will decrease as a result of discomfort and/or reduced synergistic muscle activity (hypothesis 1). Maximal fixation improved sagittal axis alignment, whereas frontal and transverse plane kinematics were unchanged (hypothesis 2). The interaction of fixation with contraction mode and angular velocity confirmed these effects (hypothesis 3).

As a consequence of the study, we recommend that initial lining up between dynamometer and joint axis should be executed when muscles are contracting isometrically. Due to the complex anatomical structure of the knee joint, a perfect three-dimensional representation by a fixed dynamometer axis is not possible. However, efforts should be made to minimise axis displacement during test contractions and thus increase measuring accuracy.

The information regarding the kinetic and kinematic relationships is important for scientists as well as clinicians in order to ensure a functional loading on the involved biological tissues and to put measurement results into perspective.

Acknowledgements

The present study was not funded. The authors would like to thank all subjects who volunteered to participate in this study and demonstrated great motivation and commitment.

Conflict of interest

All authors precluded any financial and personal relationships with other people or organisations that could inappropriately influence their work.

References

[1] Churchill DL, Incavo SJ, Johnson CC, Beynnon BD. The transepicondylar axis approximates the optimal flexion axis of the knee. Clin Orthop Relat Res. 1998 Nov; (356): 111-8.

[2] Bull AM, Amis AA. Knee joint motion: description and measurement. Proc Inst Mech Eng H. 1998; 212(5): 357-72.

[3] Smidt GL. Biomechanical analysis of knee flexion and extension. J Biomech. 1973 Jan; 6(1): 79-92.

[4] Hollister AM, Jatana S, Singh AK, Sullivan WW, Lupichuk AG. The axes of rotation of the knee. Clin Orthop Relat Res. 1993 May; (290): 259-68.

[5] Reimann U, Verdonck AJ, Wiek M. The influence of joint displacement on torque, angle and angular velocity during isokinetic knee extension/flexion. Theoretical considerations. Isokinet Exerc Sci. 1997; 6(4): 215-21.

[6] Arampatzis A, Morey-Klapsing G, Karamanidis K, DeMonte G, Stafilidis S, Bruggemann GP. Differences between measured and resultant joint moments during isometric contractions at the ankle joint. J Biomech. 2005 Apr; 38(4): 885-92.

[7] Keating JL, Matyas TA. The influence of subject and test design on dynamometric measurements of extremity muscles. Phys Ther. 1996 Aug; 76(8): 866-89.

[8] Verdonck AJ, Reimann U, Wiek M. The influence of joint displacement on torque, angle and angular velocity during isokinetic knee extension/flexion. An experimental investigation. Isokinet Exerc Sci. 1997; 6(4): 223-33.

[9] Houweling TAW, Hamzeh MA. Does knee joint alignment with the axis of the isokinetic dynamometer affect peak torque? Isokinet Exerc Sci. 2010; 18(4): 217-21.

[10] Croisier JL, Ciavatta P, Forthomme B. Influence of the dynamometer and knee joint axis of rotation alignment on the isokinetic measurements. Isokinet Exerc Sci. 2005; 13(1): 3-4.

[11] Herzog W. The relation between the resultant moments at a joint and the moments measured by an isokinetic dynamometer. J Biomech. 1988; 21(1): 5-12.

[12] Kaufman KR, An KN, Chao EY. A comparison of intersegmental joint dynamics to isokinetic dynamometer measurements. J Biomech. 1995 Oct; 28(10): 1243-56.

[13] Hart DL, Stobbe TJ, Till CW, Plummer RW. Effect of trunk stabilization on quadriceps femoris muscle torque. Phys Ther. 1984 Sep; 64(9): 1375-80.

[14] Stumbo TA, Merriam S, Nies K, Smith A, Spurgeon D, Weir JP. The effect of hand-grip stabilization on isokinetic torque at the knee. J Strength Cond Res. 2001 Aug; 15(3): 372-7.

[15] Magnusson SP, Geismar RA, Gleim GW, Nicholas JA. The effect of stabilization on isokinetic knee extension and flexion torque production. J Athl Train. 1993 Fall; 28(3): 221-5.

[16] Otten R, Whiteley R, Mitchell T. Effect of subject restraint and resistance pad placement on isokinetic knee flexor and extensor strength: Implications for testing and rehabilitation. Sports Health. 2013 Mar; 5(2): 137-42.

[17] Weir JP, Evans SA, Housh ML. The effect of extraneous movements on peak torque and constant joint angle torque-velocity curves. J Orthop Sports Phys Ther. 1996 May; 23(5): 302-8.

[18] Hanten WP, Ramberg CL. Effect of stabilization on maximal isokinetic torque of the quadriceps femoris muscle during concentric and eccentric contractions. Phys Ther. 1988 Feb; 68(2): 219-22.

[19] Ayala F, De Ste Croix M, Sainz de Baranda P, Santonja F. Absolute reliability of hamstring to quadriceps strength imbalance ratios calculated using peak torque, joint angle-specific torque and joint ROM-specific torque values. Int J Sports Med. 2012 Nov; 33(11): 909-16.

[20] Alt T, Knicker AJ, Strüder HK. Factors influencing the reproducibility of isokinetic knee flexion and extension test findings. Isokinet Exerc Sci. 2014; 22(4): 333-42.

[21] Narici MV, Sirtori MD, Mastore S, Mognoni P. The effect of range of motion and isometric pre-activation on isokinetic torques. Eur J Appl Physiol Occup Physiol. 1991; 62(3): 216-20.

[22] Wilhite MR, Cohen ER, Wilhite SC. Reliability of concentric and eccentric measurements of quadriceps performance using the KIN-COM dynamometer: The effect of testing order for three different speeds. J Orthop Sports Phys Ther. 1992; 15(4): 175-82.

[23] Rothstein JM, Lamb RL, Mayhew TP. Clinical uses of isokinetic measurements. Critical issues. Phys Ther. 1987 Dec; 67(12): 1840-4.

[24] Blazquez IN, Warren BL, O'Hanlon AM, Silvestri LR. An adequate interset rest period for strength recovery during a common isokinetic test. J Strength Cond Res. 2013 Jul; 27(7): 1981-7.

[25] Cohen J. Statistical power analysis for the behavioral sciences. 2nd ed. Hillsdale, NJ: Erlbaum, 1988.

[26] Worrell TW, Denegar CR, Armstrong SL, Perrin DH. Effect of body position on hamstring muscle group average torque. J Orthop Sports Phys Ther. 1990; 11(10): 449-52.