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The Influence of the Calculation Method on Knee Angle Trajectories and Angle-Specific Force in Multi-Joint Isokinetic Leg Extensions

Der Einfluss der Berechnungsmethode auf Kniewinkelverläufe und winkelspezifische Kraft in mehrgelenkigen isokinetischen Beinstreckungen

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Summary

- **Problem:** Since segment lengths of the lower extremities influence joint kinematics in multi-joint movements, anthropometric standardization seems necessary to study the force-length-velocity relationships of muscles in vivo. Mathematical approaches to calculate the needed linear velocities for the desired angular kinematics from individual anthropometric data exist and are in use. Nevertheless, this approach does not account for possible shifts due to cushion padding and soft tissue compression.
- **Methods:** 38 physical education students (31 male, 7 female, 24±4.32 years, 175.93±7.92 cm, 74.93±10.86 kg) participated in this investigation. Knee-angles and angle-specific force during multi-joint isokinetic leg extensions derived from an anthropometric model were compared to corresponding knee angles and forces derived from optical marker tracking for two different linear velocities (0.1 m/s and 0.7 m/s).
- **Results:** The results show significant differences ($p < 0.05$) in knee angles and angle-specific forces for multi-joint isokinetic leg extensions with 0.1 m/s and no significant differences for movements with 0.7 m/s.
- **Discussion:** Studies investigating force-length-velocity relationships during multi-joint leg extensions should implement optical measurement to eliminate the effects of shifts due to cushion padding and soft tissue compression especially when working with slow linear velocities. The possibility of a device-specific correction for the anthropometric model should be addressed in further research.

Zusammenfassung

- **Problem:** Da die Segmentlängen der unteren Extremität die Gelenkkinematik bei mehrgelenkigen Bewegungen beeinflussen, erscheint eine anthropometrische Standardisierung erforderlich, um muskuläre Kraft-Längen-Geschwindigkeits-Relationen in vivo zu untersuchen. Mathematische Ansätze zur Berechnung der notwendigen linearen Geschwindigkeiten für die gewünschte Winkelkinematik aus individuellen anthropometrischen Daten existieren und sind in Verwendung. Allerdings lassen diese Modelle mögliche Verschiebungen durch Kompression von Sitzpolsterung und Körpergewebe unberücksichtigt.
- **Methoden:** 38 Sportstudenten (31 männlich, 7 weiblich, 24±4.32 Jahre, 175.93±7.92 cm, 74.93±10.86 kg) nahmen an der Untersuchung teil. Kniewinkel und winkelspezifische Kräfte abgeleitet aus einem anthropometrischen Modell wurden den entsprechenden Kniewinkeln und Kräften erhoben mittels optischem Markertracking während mehrgelenkiger isokinetischer Beinstreckungen bei zwei verschiedenen linearen Geschwindigkeiten (0.1 m/s und 0.7 m/s) gegenübergestellt.
- **Ergebnisse:** Die Ergebnisse zeigen signifikante Unterschiede ($p < 0.05$) für Kniewinkel und winkelspezifische Kraft während mehrgelenkigen isokinetischen Beinstreckungen mit 0.1 m/s. Für 0.7 m/s konnten keine signifikanten Unterschiede festgestellt werden.
- **Diskussion:** Studien, welche die Kraft-Längen-Geschwindigkeits-Relationen bei mehrgelenkigen Beinstreckungen untersuchen, sollten optische Messmethoden implementieren, um die Auswirkungen von Verschiebungen durch Kompression von Sitzpolsterung und Körpergewebe zu eliminieren. Besonders wichtig erscheint dies bei der Arbeit mit langsamen linearen Geschwindigkeiten. Die Möglichkeit einer gerätespezifischen Korrektur für anthropometrische Modelle sollte in weiteren Untersuchungen thematisiert werden.

KEY WORDS:
Strength Testing, Force-Length Relationship, Force-Velocity Relationship

SCHLÜSSELWÖRTER:
Kraftdiagnostik, Kraft-Längen-Relation, Kraft-Geschwindigkeits-Relation

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Introduction

Isokinetic dynamometry is a widely used method to study muscle function. Several parameters have been extracted from isokinetic measurements and examined over the past decades with peak torque being the most reliable and therefore most frequently used one (14). In single-joint isokinetic measurements, angle-specific torque and the angle of peak torque have shown large variability and low reliability and are therefore not recommended for use (2, 23). These considerable variabilities are believed to be the result of the limb segments' movement relative to the dynamometer's axis of rotation caused by soft tissue compliance, padding and stabilization of the participant (3). Sorensen et al. (35) investigated the shift of the knee axis during concentric contractions with various angular velocities and observed a downward

Table 1

Knee-angles retrieved from the anthropometric model and marker-based tracking in multi-joint isokinetic leg extensions with 0.1 m/s. *=significantly different from corresponding angle of the anthropometric model (p<.01).

ANTHROPOMETRIC MODEL [°]		MARKER MODEL [°]		% DIFF
MEAN	SD	MEAN	SD	
90.16	0.32	100.80*	5.60	11.81
100.05	0.04	112.57*	4.00	12.51
110.04	0.04	122.90*	3.26	11.69
120.03	0.05	133.24*	2.54	11.01
130.01	0.05	144.88*	2.17	11.44
140.00	0.06	157.61*	3.22	12.58
150.06	0.11	162.81*	4.04	8.50
160.01	0.06	161.99	4.19	1.23

Table 2

Knee-angles retrieved from the anthropometric model and marker-based tracking in multi-joint isokinetic leg extensions with 0.7 m/s. *=significantly different from corresponding angle of the anthropometric model (p<.01).

ANTHROPOMETRIC MODEL [°]		MARKER MODEL [°]		% DIFF
MEAN	SD	MEAN	SD	
90.63	0.26	92.67	3.51	2.26
100.28	0.23	102.96	3.09	2.67
110.34	0.28	112.27	3.45	1.75
120.18	0.08	120.97	3.43	0.66
130.34	0.20	129.90	3.71	-0.34
140.14	0.44	138.83	4.31	-0.93
150.42	0.41	147.51	4.43	-1.93
160.42	0.61	154.88	4.37	-3.45

Table 3

Peak force, knee angle at peak force and knee angular velocity at peak force retrieved from the anthropometric model and marker-based tracking. * = significantly different from anthropometric model; + = significantly different from 0.7 m/s (p < 0.01).

LINEAR VELOCITY [M/S]	ESTIMATION METHOD	PEAK FORCE [N]		Ω [RAD/S]		KNEE ANGLE AT PEAK FORCE [°]	
		MEAN	SD	MEAN	SD	MEAN	SD
0,1	Marker	4470.81^{+}	1303,90	0.88^{+}	0,51	145.57^{*+}	8,41
	Anthropometric model			0.56^{+}	0,07	130,08	5,70
0,7	Marker	3011,45	340,79	3,53	0,50	130,50	5,36
	Anthropometric model			3,86	0,26	130,85	4,98

movement of the knee caused by soft tissue and padding compression as well as pelvis movement that resulted in errors in knee angles of up to 33°. Alt et al. (1) performed a kinematic analysis for eccentric knee flexion and concentric knee extension with 150 °/s in prone and supine positions. They observed a reduction in range of motion of 17° for concentric knee flexion and 21° for eccentric knee extension from the preset of 110°. This led to a reduced mean isokinetic velocity of 121 °/s for concentric knee extension and 122 °/s for eccentric knee flexion, respectively due to a considerable shift of the knee joint axis.

Over the last decades, multi-joint isokinetic evaluation gained interest because it enables investigation of muscle function in multi-joint tasks that are considered to being more closely correlated to actual everyday human movement than single-joint laboratory experiments (19, 20). Because of the varying segment kinematics with linear isokinetic velocities due to anthropometric differences, Hahn et al. (19) developed a method to calculate the needed linear parameters to provide for standardized angular velocities of the involved joints based on anthropometric data. Maximal force values obtained using this method have been shown to be of high reliability (13). The proposed method has since been used in several investigations regarding the torque-angle relationship and residual force enhancement in multi-joint tasks (17, 18, 20) as well as performance testing in skiing athletes (31) and motion analysis in rowers (10, 11, 12).

Dvir & Müller (15) emphasized the need for such an anthropometric standardization in multi-joint isokinetic leg extensions, nonetheless, to date no observations on the influence of compression of soft tissue and padding on the knee-angle trajectory in multi-joint isokinetic leg extensions with different velocities exist. When considering the measurement error in joint kinematics arising from the shift of the knee axis during single-joint testing (1, 35) and the substantial implications arising from this for the investigation of muscle function, an investigation of the measurement error in multi-joint leg extensions seems beneficial to further improve and develop adequate measurement methods. Since slow isokinetic leg extensions have shown to enable for much greater forces than fast extensions (27, 28), the linear velocity of the leg press might influence the error in knee angle trajectory caused by compression. As the results of Sorensen et al. (35) and Alt et al. (1) show, this might have significant relevance for the study of force-length-velocity relationships. Therefore, the aim of this investigation was to compare the knee angle trajectory during multi-joint isokinetic leg extensions with two different velocities detected by the use of reflective markers and estimated using anthropometric data.

Methods

The present study investigates the influence of two different calculation methods on knee angle trajectories and angle-specific force in thirty-eight physical education students. Maximum force of the knee and hip extensors was measured via an isokinetic leg press. The corresponding knee angles were tracked via reflective markers and calculated from anthropometric data. All participants completed a familiarization session consisting of the whole measurement procedure one week before the actual tests were conducted.

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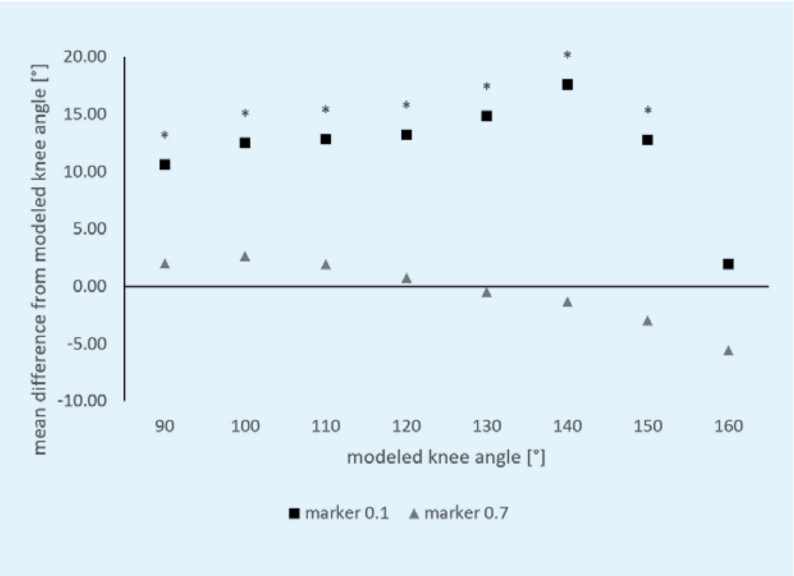

Figure 1

Mean difference between marker-based tracking and the modelled knee angles from anthropometric data. *=significant difference (p<0.05) between the anthropometric model and the marker model at 0.1 m/s.

Subjects

Thirty-eight physical education students (31 male, 7 female) participated in this investigation. Their mean age was 24±4.32 years, their mean height was 175.93±7.92 cm and their mean body mass was 74.93±10.86 kg. Each subject was informed of the experimental risks involved with this investigation. All subjects provided informed written consent. The research design was approved by the institutional review board. The study was carried out with respect to the use of human subjects and according to the Declaration of Helsinki.

Multi-Joint Isokinetic Leg Extension

Multi-joint isokinetic leg extensions were performed using the ISOMED2000 isokinetic leg press device (D&R Ferstl GmbH, Hemau, Germany) with a measuring rate of 200 Hz. The movement start was set to a knee angle of 85 degrees flexion with the movement end at a knee angle of 170 degrees (referring to 180 degrees as full extension). Movement start and end were determined during a contracted condition of the involved muscles. Maximal isokinetic force and knee angle trajectory were determined bilaterally at movement velocities of 0.1 m/s and 0.7 m/s. These velocities were chosen because they have been used for investigation of force performance before and show different relationships with jumping, sprinting and squatting 1RM (27, 28). The slow condition was measured first followed by the fast condition as recommended by Perrin (30) as sequence for isokinetic testing. For each movement velocity, 5 attempts with an inter-repetition rest of at least 30 s were measured after an individual warmup consisting of several trials with the respective measurement velocity. The participants started each attempt individually with no command given by the examiner.

Knee Angle Trajectory

The trajectory of the knee angle was estimated using two different methods.

For method one, the trajectory of the knee angle was estimated from the position data of the leg press device using the participants' shank and thigh length measured with a tape measure. A comparable method was described in detail by Hahn et al. (19).

For method two, reflective markers with a diameter of 0.5 cm were placed on the lateral malleolus, the lateral femoral condyle and the greater trochanter. Leg extensions were tracked with 200 Hz using a Sony NEX-FS700RH camera (Sony Corporation, Tokio, Japan) with a resolution of 1920x1080px progressive. The statically calibrated object space had a height of 1.398 m and a width of 2.469 m, which resulted in a pixel resolution of 1.25 mm. The videos were analysed using the software SIMI MOTION 9.1.1 (Simi Reality Motion Systems GmbH, Unterschleißheim, Germany).

Data Analysis

For each velocity the trial showing the greatest peak force of each participant was analysed. The data was analysed using SPSS 11.5 (SPSS, Inc., Chicago, IL, USA). The two different knee-angle estimations were synchronized via the start of the isokinetic movement phase. The first data points of the machine position data and the video that reflected the isokinetic velocity were matched. Knee angles of 90, 100, 110, 120, 130, 140, 150, and 160 degrees from the anthropometric estimation model were compared to the corresponding angles derived from marker tracking. Angle-specific forces for both models were analysed for knee angles of 100, 110, 120, 130, 140, 150, and 160 degrees. Additionally, peak force at both linear velocities, the knee angle at peak force as well as knee angular velocity at peak force for each model were investigated. Kolmogorov-Smirnov test showed a normal distribution of the data. The homogeneity of variance between groups was confirmed using the Levène test for the angle-specific force values and peak force, but not for the knee-angle data. For comparisons between the force values, a 1-factorial analysis of variance was performed. For comparisons between the knee-angles and knee angular velocities of the different models, a Welch-ANOVA was performed. When statistically significant F values were returned, the Scheffé's test was used for further post hoc analyses of both tests.

Results

The reliabilities of the force measurements of the present study were calculated from the two best attempts and revealed values of ICC=0.921 for 0.1 m/s and ICC=0.970 for 0,7 m/s. The Welch- ANOVA of the knee-angles in multi-joint isokinetic leg extensions with 0.1 m/s showed significant differences (p<.01) between the applied models except for a knee-angle of 160 degrees (table 1). The analysed angles with significant differences between the methods show differences between 8.5% and 12.6%.

The results in table 1 show that marker-based tracking of the 125 knee-angle reveals a non-uniform trajectory throughout multi-joint isokinetic leg extensions with 0.1 m/s. The Welch-ANOVA of the knee-angles in multi-joint isokinetic leg extensions with 0.7 m/s revealed no significant differences between the applied models (table 2). The analysed angles show differences between -3.5% and 2.7%.

Figure 1 illustrates the mean difference between the knee angle trajectory of the different velocities and the modeled knee angle. Marker-based tracking reveals a rather uniform trajectory throughout multi-joint isokinetic leg extensions at 0.7 m/s with small differences to the modeled knee angles while a non-uniform trajectory with knee angle differences of up to 18° can be observed for extensions with 0.1 m/s.

The ANOVA of the angle-specific force in multi-joint isokinetic leg extensions with 0.1 m/s showed significant differences (p<.01) between the applied models except for a knee-angle of 140 degrees (figure 2). The analysed angles with significant differences between the methods show differences between -38.7% and 282.7%.

The two applied models produce different trajectories in multi-joint isokinetic leg extensions with 0.1 m/s. Marker-based tracking of the knee-angle reveals a rightward shift of the force-angle-curve compared to the anthropometric model.

The ANOVA of the angle-specific force in multi-joint isokinetic leg extensions with 0.7 m/s showed significant differences (p<.01) between the applied models only at a knee-angle of 160 degrees (figure 3).

The results of the angle-specific force show a mostly uniform trajectory throughout multi-joint isokinetic leg extensions with 0.7 m/s for the two applied models.

The data of velocity-specific peak force, knee angle and knee angular velocity at peak force (table 3) show significantly greater peak force at 0.1 m/s compared to 0.7 m/s. Knee angular velocity at peak force was significantly lower in the slow linear condition showing no differences between the estimation methods. Knee angle at peak force revealed no differences between the estimation methods at 0.7 m/s and no difference between the linear velocities for the anthropometric model. The knee angle at peak force estimated by reflective markers at 0.1 m/s was significantly greater than the knee angle at peak force by the anthropometric model as well as both knee angles at 0.7 m/s.

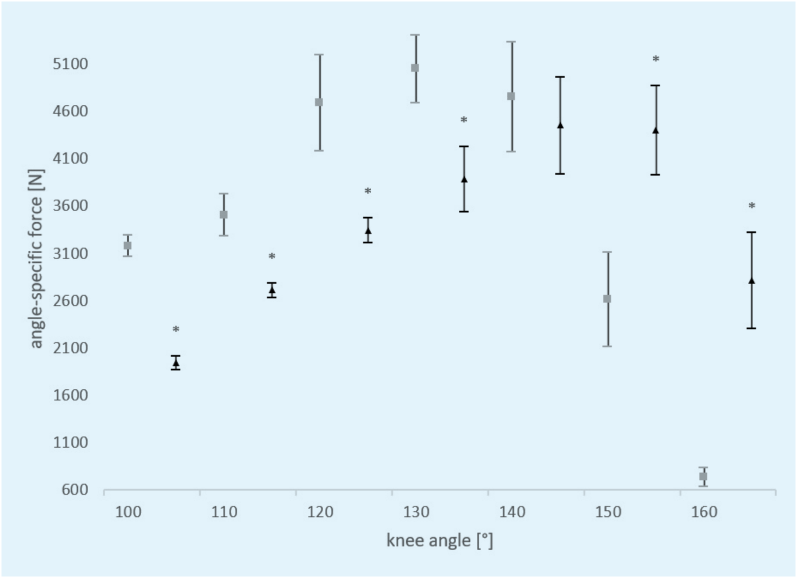

Figure 2

Angle-specific force in multi-joint isokinetic leg extensions with 0.1 m/s retrieved from the anthropometric model (squares) and marker-based tracking (triangles). *=significant difference (p<0.05) between the models.

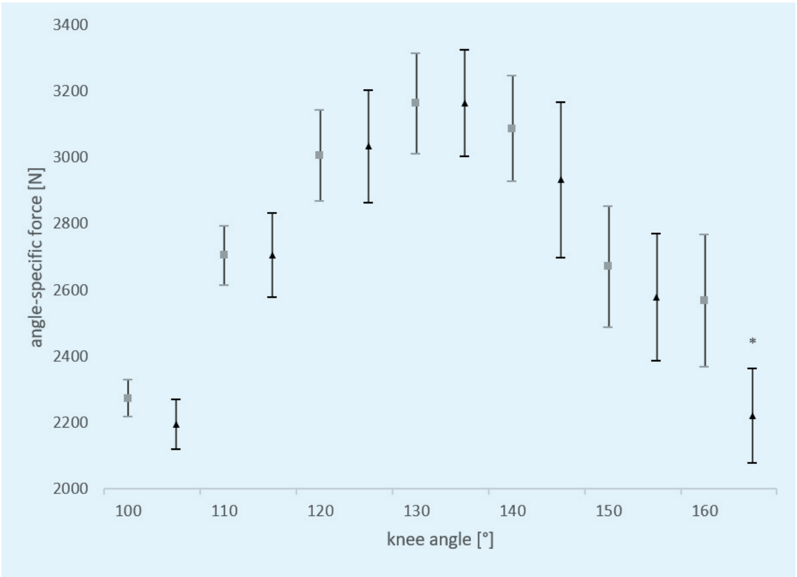

Figure 3

Angle-specific force in multi-joint isokinetic leg extensions with 0.7 m/s retrieved from the anthropometric model (squares) and marker-based tracking (triangles). *=significant difference (p<0.05) between the models.

Discussion

The present study revealed significant differences in knee angles and angle-specific force during multi-joint isokinetic leg extensions either calculated via an anthropometric model or derived from marker-based tracking for a slow linear velocity. With a faster linear velocity, no significant differences could be observed.

Since the different applied models showed significant differences in variance, considerations regarding the accuracy seem profitable. The anthropometric approach considers the involved joints as simple hinge joints and does not account for a possible shift of the rotational axes (19). So, for this data, only the accuracy of the isokinetic device has to be taken into account. In addition to the measuring rate of 200 Hz, the manufacturer states an accuracy of 0.5% full scale for the measured force and a resolution of 0.5 cm for the position data of the leg press sleigh. For the marker-based detection of the knee angle it has to be noted that skin-markers produce reliable data but do not directly reflect the movement of the underlying bone structure due to skin movement artifacts. For example, Benoit et al. (5) report a standard error of measurement of 2.5° for walking.

The knee angle trajectories of the different methods show great accordance for 0.7 m/s, whereas for 0.1 m/s significant differences can be observed. In the slow condition, the marker-based estimation shows greater changes in the knee-angle than the anthropometric model at the beginning and the end of the movement. Visual inspection of the obtained videos for the marker-based estimation indicate a horizontal movement of the hip marker towards the back rest at the beginning of the contraction and towards the leg press sled at the end of the knee extension in the slow condition. Since slow isokinetic velocities enable for greater torque or force (13, 27, 28, 30), it can be hypothesized, that the slow velocity led to greater compression of the cushion padding of the back rest and the participants' soft tissue that caused a horizontal shift of the hip joint.

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Because of this mechanism, maximum extension of the knee joint occurred considerably earlier during the movement than in the fast condition. Maximum extension as well as the following decompression of the back rest and soft tissue being reached earlier might have led to the slight decrease of the knee angle at the end of the slow extension. This theory is further supported by the percentage difference between the models illustrated in figure 1 showing a decreasing difference towards the end of the movement. In accordance with this possible explanation, the present study also observed noticeably greater forces in leg extensions with 0.1 m/s than with 0.7 m/s as well.

This assumption is underlined further by the angle-specific forces, showing significant differences between the two models only for 0.1 m/s. Therefore, the lower forces with higher velocities should lead to lower compressional forces according to Newton's third law. With slow velocities, however, the greater force production creates greater compression which leads to the observed significant differences in the knee angle. Nevertheless, it should be noted that despite the absence of significant differences in angle-specific force with 0.7 m/s, significant differences regarding the impulse might occur as a result of a possible addition of the small, insignificant differences in knee ROM and angle-specific forces and should be investigated further.

Dirnberger et al. (13) performed a reliability-study of multi-joint maximum forces obtained using the anthropometric model with knee angle-velocities of 40 °/s and 80 °/s. The selected angular velocities corresponded to translational foot velocities of 0.120–0.190 m/s and 0.240–0.380 m/s, respectively. High reliability scores could be obtained for both velocities, but the slower condition showed slightly smaller ICC values and 60-70% greater SEM than the faster extensions. A relation to greater errors in angular velocity due to greater compressional forces in the slower condition seem conceivable when the findings of the present study are taken into account.

Another important fact to consider is that the anthropometric approach models the knee as a perfect hinge joint. However, knee joint motion is guided by an axis that changes in position and orientation (6, 34, 36). In this context, it could be further hypothesized that the mechanical properties of the connective tissue might influence the amount of shift occurring regarding the knee axis. Since female sex hormones have a negative effect on collagen content of the joint capsule (21) and seem to modulate joint hypermobility and the prevalence of osteoarthritis (9), a possible sex difference in changes of the knee joint axis appears conceivable.

Regarding the peak force analysis, the slow linear condition produced significantly greater peak forces compared to the fast linear condition. This is in line with previous investigations showing similar force values with the same set up (27, 28). The slow linear condition revealed significantly lower knee angular velocities at peak force compared to the fast condition with no substantial difference between the estimation methods. This might explain previous observations that isokinetic peak force at 0.7 m/s shows greater correlations with sprinting (28) and vertical jumping performance (27). The results of Nuzzo et al. (29) indicate that 1RM in the squat and the power clean are more closely related to CMJ performance measured via jump height, peak velocity, peak power and peak force than corresponding isometric methods (isometric squat test and isometric mid-thigh pull). When considering that isokinetic peak force at 0.7 m/s displays greater correlations with squat 1RM and CMJ jump height than peak force at 0.1 m/s (27) and that the slow linear condition shows substantially slow knee angular velocities at peak force in this investigation, these results seem to match. The angular velocities during the fast linear condition of 3.53-3.86 rad/s still have to be characterized as noticeably lower than peak angular velocities as well as angular velocities at the corresponding knee angle during vertical jumping (6, 8, 32) but shows similarities to the peak angular velocities during the squat 1RM (26). When taking observations from single-joint measurements into account, where isokinetic performance of the knee extensors shows greater connections to jumping performance at high angular velocities compared to low angular velocities (22, 33), the known mechanism of slight angular changes in isometric measurements and the low angular velocities in the slow linear condition observed in the present study promote the hypothesis that slow isokinetic testing might show greater similarity to isometric than to highly dynamic muscle actions. Further research investigating muscle mechanics and neural activation patterns might clarify this hypothesis and provide a deeper insight. A possible velocity threshold could be highly valuable to optimize performance testing for performance and rehabilitation settings.

The comparisons of the knee angle trajectories derived from the two models let a velocity dependent correction appear conceivable. However, such a mathematical correction for the anthropometric model might face several challenges. Since the relevance of the hip extensors for maximum force in multi-joint movements appears to increase with intensity (4) and maximum strength is highly correlated with muscle mass (37), stronger and more muscular individuals could display higher amounts of soft tissue compression leading to grater errors in knee angle. Additionally, research from material sciences and automotive technology indicate that the mechanical properties of cushion padding change with time and usage (16, 24, 25). So, a mathematical correction for the anthropometric model would probably be specific to the single dynamometer used and change with time.

One limitation of this study is that it concentrates on the trajectory of the knee angle only. We hypothesized that the observed compression of the back rest's cushion padding and the participants' soft tissue especially in the slow condition accounted for the differences in the knee angle trajectory between the two calculation methods. Because of these observations and the fact that the contribution of the hip extensors increases with higher intensities (4), investigating the trajectory of the hip angle as well would have been interesting. Another limitation is the analysis of discrete knee angle configurations. A continuous investigation of the knee and hip angle trajectories, for example via statistical parametric mapping, might help to understand and develop measurements of multi-joint leg extensions further in the future.

Conclusions

The necessity of anthropometric standardization for multi-joint isokinetic leg extensions for the study of muscle force-length-velocity relationships outlined by Dvir & Müller (15) and Hahn et al. (19) needs to be recognized in further investigations. Nonetheless, different linear velocities might lead to different errors in the knee angle. Future investigations should address this uncertainty by implementing additional measurements of the knee angle. Since a linear velocity of 0.7 m/s showed no significant differences in the knee angle trajectory, further investigations are needed to verify whether a minimal velocity threshold exists that accounts for comparable data. Additionally, it should be verified how age and usage of isokinetic dynamometers influence the error in knee angles due to changes mechanical properties of the padding. ■

Conflict of Interest

The authors have no conflict of interest.

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