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Research article

The effects of kinetic energy on concentric and eccentric isokinetic work

Brian Boggess [1], Jeff Moffit [2]✉, Jacobo Morales [3] and Tim Anderson [3]
[1] California Department of Corrections Southern Testing Center, Rancho Cucamonga, CA, USA, [2] California State University, Bakersfield, Bakersfield, CA, USA, [3] California State University, Fresno, Fresno, CA, USA

Abstract

This investigation examined inertial effects on work output during isokinetic concentric knee extension and eccentric knee flexion. Total work (W_{total}) included work due to kinetic energy (W_{kin}), with respect to gravity (W_{grav}), and against the dynamometer (W_{dyn}). Eighteen resistance-trained participants (9 males, 9 females) performed maximal voluntary concentric (90, 150, 210, 270 deg/s) and eccentric (-150, -90, -30 deg/s) actions with the dominant leg. Differences between work measurement type (WMT), i.e., gravity-corrected work and W_{total}, were assessed. ANOVA (2 WMT x 2 mode x 2 gender x 4 speed) revealed significant main effects ($p < 0.05$) for both factors concentrically but only for WMT eccentrically. It was concluded that the effect of kinetic energy during isokinetic leg extension may elicit differences in measurement where the associated error (K_{err}) significantly increases with increasing velocity concentrically and decreases eccentrically.

Key words: Kinetic energy, kinetic error, work measurement type.

Introduction

Isokinetic work is defined as the area under the torque versus angular displacement curve (Kannus, 1992; 1994). Isokinetic torque measurements reflect only that measured against the resistance of the dynamometer (load range) after the preset velocity has been reached (Brown et al., 1995, Findley et al., 2006). Additional torque must be provided (and work accomplished) to accelerate the limb and lever arm up to the prescribed angular velocity (e.g., concentric knee extension) or control the limb and lever arm (e.g., eccentric knee extension) against gravity. Therefore, the ability of the dynamometer to record the dynamic muscular kinetics during the entire isokinetic effort is somewhat limited (Iossifidou and Balzopoulos, 1998; 2000) due to its insensitivity to the torque output during acceleration, or rate of velocity development, which occurs in the initial range of motion (ROM).

In order to account for the components of work not reported by the dynamometer, total work (W_{total}) must be expressed as a function of the work necessary to achieve the specified angular velocity (kinetic energy) and the work with respect to gravity. This initial work output against the inertial properties of the limb and lever arm is most evident at higher concentric velocities and is often marked by a delay in torque application against the resistance of the dynamometer (Winter et al., 1981; Olmo and Castilla, 2005; Findley et al., 2006).

When comparing the inertial requirements to either accelerate (concentric contraction) or control (eccentric action) the system at the specified velocity, W_{total} differs between these conditions. The kinetic energy during eccentric isokinetic actions is not a factor to be overcome by muscular effort; rather, gravity and the motion provided by the dynamometer will be responsible for the achievement of kinetic energy (Iossifidou and Baltzopoulos, 1996). Muscular activity is needed to ensure the limb descends at the specified speed, yet the dynamometer will not be sensitive to the measures of torque or work necessary for this control.

Additionally, the confounding effect gravity has on isokinetic torque measurements has traditionally been dealt with by adding the torque due to gravity of a system when the motion requires movement against gravity and the subtraction of torque due to gravity on a system when gravity assists a motion (Nelson and Duncan, 1983). Modern dynamometers have gravity correction software options; however, the correction standard only considers the effect of gravity on torque due to the position of the limb and lever arm and is insensitive to the amount of work that must be generated against the inertial properties of the limb and lever across angular velocities and in the different modes of contraction (Kellis and Baltzopoulos, 1996).

Since the simple correction for gravity may be inadequate a more complete description of muscular effort during isokinetic contraction should include a consideration of kinetic energy (KE). When applied to conditions of isokinetic dynamometry, the calculation of KE must include values of the inertia for both the limb and lever arm and the angular velocity to which the system will be accelerated. Thus, with the inclusion of the components of KE, the additional work requirement during the performance of isokinetic actions can be addressed.

Therefore, the purpose of this investigation was to assess the isokinetic concentric and eccentric total work output (W_{total}) of the knee extensors by considering the work required to overcome the inertia and weight of the limb and lever arm system. Additionally, the estimated W_{total} was compared to the kinetic work (W_{kin}) to determine the extent of kinetic error (K_{err}) related to movement types, contraction velocity, and gender.

Methods

All isokinetic torque and work output were measured on a Biodex System 2 dynamometer (Biodex Corp., Shirley, NY), which has been shown to be a reliable isokinetic

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measurement device (Brown et al., 1993; 2005). The participants included 9 men (age 25.4 ± 5.3 years, height 1.77 ± 0.06 meters and mass 85.9 ± 15.1 kg) and 9 women (age 22.8 ± 55 years, height 1.69 ± 0.09 meters, and mass 65.4 ± 10.0 kg). All participants were without history of musculoskeletal or joint pathology about the knee. All subjects had at least 6 months of resistance training experience and each was currently involved in such a program. All gave written informed consent consistent with the policies of the Committee on the Protection of Human Subjects at California State University, Fresno

Familiarization with the Biodex dynamometer and the recording of anthropometric measures occurred in a first meeting. A subsequent meeting was used to collect the maximal isokinetic data included in the statistical analyses. The subjects (shoeless) were seated and stabilized with manufacturer-supplied straps while the axis of the dynamometer was aligned with the femoral epicondyles. The length of the lever arm was adjusted to the nearest half-inch mark such that the distal shin pad and strap were secured just proximal to the medial malleolus, but proximal enough to allow for the required maintenance of a neutral ankle position.

Measurements of the physical properties of the Biodex lever arm detached from the powerhead involved a trip balance (W.M. Welch Manufacturing, Chicago, IL) to measure its mass. A photogate timer (Pasco Scientific Model ME-9215A, Roseville, CA) was used to measure its period of oscillation. The Biodex also served as the instrument for measuring the moment of the lever arm. In order to estimate the segmental moments of inertia, length and circumference measurements were made of the shank and foot (Yeadon and Morlock, 1989; Plagenhoef et al., 1983).

The test speeds included concentric angular velocities of 90, 150, 210, and 270 deg/s and eccentric velocities of -150, -90, -30 deg/s. It was evident from pilot study that some participants could exceed the eccentric torque limit. Therefore, the eccentric speeds for which participants in the present study were able to achieve this torque limit were not included in the data analysis because of the departure from isokinetic conditions. Acceleration buffering at the end ranges of motion was set to "hard" (zero) to maximize the portion of the movement which remains isokinetic (Iossifidou and Baltzopoulos, 1996).

The starting position for concentric tests was selected at the point where the limb and lever came to rest while the participant relaxed the thigh and leg musculature forming a point at which there was no net torque on the system. The joint angle was not controlled and therefore was not measured although it approximated 90 degrees. The concentric end range of motion for each participant was defined as a point which approached full knee extension. The mean angular displacement of the lever arm recorded by the Biodex during concentric tests was 70.7 (± 4.2) degrees. To facilitate the return of the limb to the starting position, the opposite (flexion) direction velocity was set at 180 deg/s for concentric bouts. The angular displacement of the lever arm for eccentric tests was standardized at 60 degrees for all participants. This ROM was chosen in conjunction with a starting position deliberately short of full extension (zero degrees flexion) because the Biodex requires voluntary effort (activation torque) to initiate motion in the eccentric mode.

In preparation for each velocity during concentric and eccentric tests, two sub maximal efforts were performed where the participant was instructed to provide approximately 80% and 90% maximal voluntary efforts. Thirty seconds rest was given between the end of the two preparatory efforts and the start of the three sequential maximum effort trials. For each testing velocity, the best work repetition recorded among these three maximal attempts was used for data analysis. In order to minimize possible effects of carry-over fatigue, the order of test velocities was randomized and one-minute rest periods were given between the conclusion of a test velocity and the start of the next velocity (Colliander and Tesch, 1989; Griffin et al., 1993). Because maximal eccentric efforts may affect subsequent maximal concentric efforts, concentric testing preceded eccentric testing (Koutedakis et al., 1995; Mohtadi et al., 1990; Poulin et al., 1992; Rizzardo et al., 1988).

Limb moments were estimated from parameters given by Plagenhoef et al. (1983). The mass of the lever arm (2.69 kg) was determined using the trip balance. The centers of mass for the lever arm were determined by balancing it on a wedge at each distinct length used in data collection sessions. The position of the balance point relative to the axis of rotation was recorded for each length. For each participant, the work with respect to gravity of the limb-lever system was calculated as follows:

$$W_{grav} = mgr_T\,(1 - \cos\theta) \qquad (1)$$

where m is the mass of the system (shank, foot, and lever arm), g is the acceleration due to gravity, r_T *is the distance from the axis of rotation to the system center of mass (i.e., the total system radius of rotation), and* θ *is the angle of displacement from vertical (where the net torque equals zero).*

The total system radius of rotation (r_T) was determined by constructing a geometrical model according to the weighted position of each component (shank, foot, and lever arm) in the plane of motion. The centers of mass for the lever arm were considered to lie along the same line within the plane of motion since the axes of each are nearly parallel when the leg is secured in the distal pad and strap.

The determination of the kinetic energy associated with the limb-lever system depends on the total moment of inertia for the limb-lever system (the sum of that for the shank, foot, and lever arm) and the square of the preset isokinetic velocity: $KE = \frac{1}{2}I\omega^2$. The values of I for the limb segments were estimated; whereas, those for the lever arm were determined experimentally. As the moment of inertia of a rotating body depends on the distribution of mass and its distance from the axis of rotation, the determination of the moment of inertia (I) for complex objects involves the summation of the product of unequal portions of the total mass in relation to their square distance from the axis of rotation (Sternheim and Kane, 1991). As each increment of mass (m) is a certain distance (r) from the axis, then I was found by the integral: $I = \int r^2 dm$.

An alternate method was used for determining the moment of inertia for a rigid body by measuring its moment and period of oscillation with the relationship: $I = T^2M / 4\pi^2$ (Tipler, 1991) where T is the period of oscillation and M is the moment. For each unique lever arm length used in this study, the period of oscillation was determined with the photogate timer and the moment was determined on the Biodex dynamometer in “Isometric” mode with the lever arm in a horizontal position.

By substituting the variables for kinetic energy and potential energy into the expression for W_{total}, the total work for each experimental condition was calculated from the following:

$$W_{total} = mgr_T\,(1\text{-}\cos\theta) \pm ½[(T^2M / 4\pi^2) + I_{limb}]\,\omega^2 + W_{dyn} \qquad (2)$$

where m, r_T, and I_{limb} (the estimated limb moment of inertia) were dependent on the participant’s characteristics; θ was dependent on the mode and positioning of the participant; T and M were dependent on lever arm length; and ω was preset at the dynamometer. Depending on whether the condition was concentric or eccentric, the W_{kin} (middle term) was either added to or subtracted from the W_{grav} (first term), respectively.

Because isokinetic parameters are often reported in relation to a correction factor for the influence of gravity, standard work (W_{std}) is defined as the sum of the W_{grav} and that recorded by the dynamometer (W_{dyn}). W_{total} was used in the definition of two other parameters employed in this study: kinetic error (K_{err}) and work measurement type (WMT). Kinetic error was defined as the ratio W_{kin}/W_{total} and represented the proportion of total work either over- or underestimated when W_{kin} is not considered. W_{total} in combination with W_{std} comprised the WMT group and were compared for the purpose of identifying differences between these two measurement methods.

Results

Work measurement type (see Table 1) expressed as mean work output measurements (W_{total}, W_{std}, W_{dyn}) across speeds for males and females are shown in Figures 1 and 2, respectively. Although the statistical analyses of work type included only W_{total} and W_{std}, W_{dyn} appears in the figure as referent to the amount of uncorrected dynamometer work. Four-way (2 WMTs x 2 modes x 2 genders x 4 speeds) analysis of variance (ANOVA) was performed to determine interactions that involved modes and genders. For concentric tests, both main effects and their interaction were significant ($p < 0.05$) in both males and females. Analysis of the eccentric work data revealed a significant main effect ($p < 0.05$) for WMT only and significant interaction ($p < 0.05$) for both genders. Comparisons of work measurements types were conducted for both genders to reveal if the method of reporting work output introduced significant differences between measures of work at individual speeds. Three-way ANOVA (2 WMT x 2 genders x 4 speeds) showed significant differences ($p < 0.005$) for all paired work measurement types across all speeds and for both modes and genders except at the lowest speeds (30 deg/sec eccentric and 90 deg/sec concentric) between genders ($p > 0.05$). The change in work output, which was introduced by adding W_{kin} to W_{std}, increased with greater concentric angular velocities. For eccentric data, an opposite trend was noted where differences were negative and decreased with increasing velocities.

Kinetic error (K_{err}) was defined as the ratio W_{kin}/W_{total}. Descriptive statistics for this variable, expressed as a percent, are given in Table 2. Two-way ANOVA (gender x speed) for concentric data and eccentric data demonstrated that all main effects and interactions were significant ($p < 0.05$). For concentric tests, Duncan Multiple Range Tests showed significant differences between genders ($p < 0.05$) only at the two fastest velocities (210 and 270 deg/s). For eccentric speeds, a between-gender difference was observed only at the fastest velocity (150 deg/s). In addition, post-hoc comparisons showed that K_{err} significantly increased ($p < 0.05$) with increasing velocity for both genders.

The magnitude of the differences across speeds is notable. As shown in Table 1, the differences due to W_{kin} at the slowest speeds were marginal. However, at the fastest concentric speed (270 deg/s), the percent difference was, on average, 6.2% for males and 9.1% for females. This trend is consistent with the presence of significant interactions (WMT by speed) within both modes and genders in that the differences in work measurements were not equivalent across speeds. The most direct explanation for this relationship, where the proportion of W_{kin} compared to W_{total} increases with increasing speed, relates to (a) the fact that W_{kin} is proportional to the square of the

Table 1. The effect of W_{kin} on W_{total} expressed as the mean difference between W_{total} and W_{std} and the percent change from W_{std} to W_{total}.

	Angular Velocity (deg/s)						
	Eccentric			Concentric			
	-150	-90	-30	90	150	210	270
Males (J)							
Mean	-2.30	-.80	-.10	.70	2.50	4.90	8.00
SD	.21	.52	.04	.15	.42	.83	1.37
%	1.0	0.4	0.0	0.5	1.5	3.3	6.2
Females (J)							
Mean	-2.00	-.70	-.10	.70	2.00	3.90	6.40
SD	.55	.20	.02	.19	.55	1.07	1.77
%	1.5	.5	.1	.6	2.0	4.8	9.1

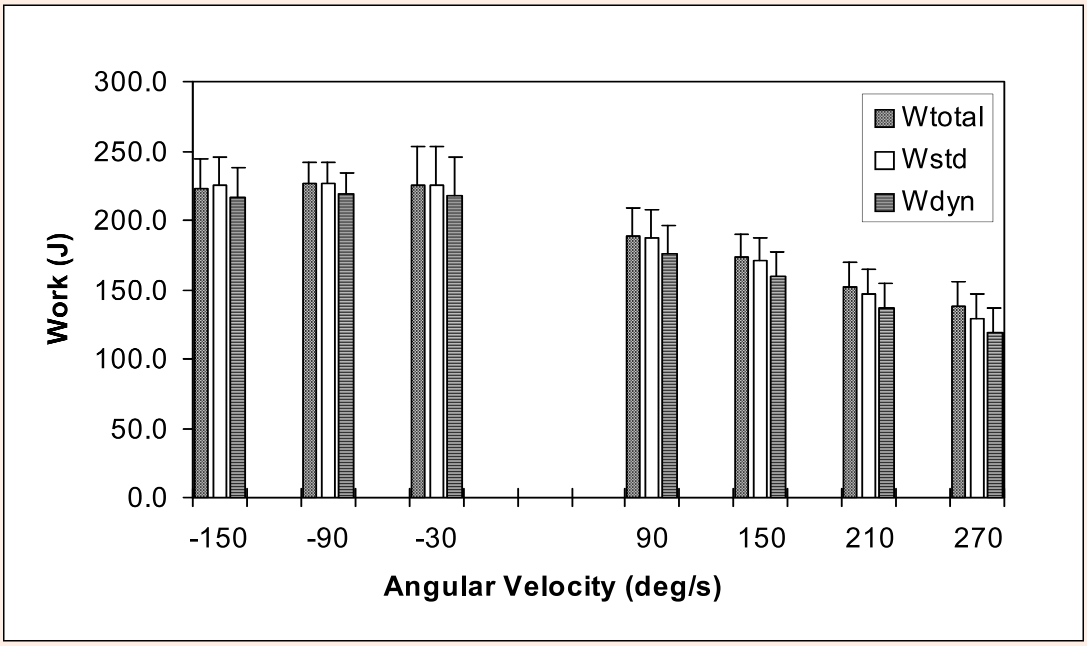

Figure 1. Mean measures of work for males.

angular velocity and (b) the tendency for W_{dyn} to be inversely proportional to the concentric velocity.

Direct comparison between concentric and eccentric modes in the present study was not appropriate for four main reasons: (a) the range of speeds tested was not the same, (b) the ranges of motion were defined differently, (c) eccentric actions required an activation force prior to movement, and (d) the role of W_{kin} changes across modes in determining W_{total}. The maximal eccentric speed available on the Biodex used in this study was -150 deg/s. Since it was an intention to explore concentric speeds beyond this eccentric speed limit, speeds between modes could not be paired across the velocity spectrum examined. Different ranges of motion were chosen due to the distinct operation of the Biodex between modes. In addition, the activation force requirement during eccentric motions may have introduced dissimilar testing conditions between modes. Measures of average torque have been reported to increase with increasing activation forces along with a tendency for larger effects with eccentric actions and at higher velocities (Kramer et al., 1991). In the present study, the combined effect of ROM and activation force may have provided conditions of differential opportunity to do work between modes. Therefore, the analysis of modes remained distinct.

Due to the inability to collect eccentric data on all

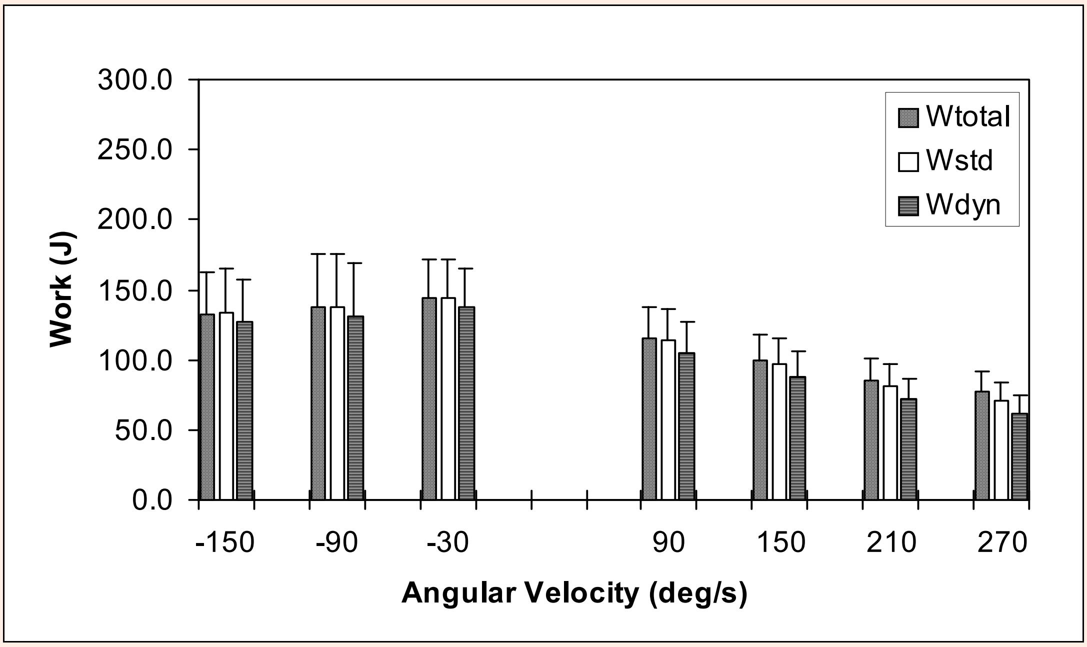

Figure 2. Mean measurements of work for females.

Table 2. Magnitude of Kinetic Error (K_{err}) expressed as a percentage based on the ratio between W_{kin}/W_{total}.

	Angular Velocity (deg/s)						
	Eccentric			Concentric			
	-150	-90	-30	90	150	210	270
Males (J)							
Mean	1.050	.370	.040	.480	.440	3.220	5.930
SD	.130	.025	.005	.104	.258	.551	1.327
Females (J)							
Mean	1.530	.550	.060	.630	2.010	4.560	8.420
SD	.380	.212	.019	.159	.402	.999	1.761

the male participants in the present study, the related statistical analysis may have been less robust than for the concentric data. This shortcoming was not related to any limitations of the participants involved. On the contrary, 3 males had sufficient strength to surpass the eccentric torque limit of the Biodex dynamometer. If another population with similar mean anthropometric dimensions but lower mean isokinetic leg extension strength (non-strength trained) had been selected for this study, the magnitude of the difference between total and standard isokinetic work would have been greater.

The standard rule for gravity correction during eccentric isokinetics is the same for concentric: gravity effect torque is subtracted where gravity assists and added where gravity opposes the motion (Kramer et al., 1991; Westing and Seger, 1989). Therefore, for concentric and eccentric isokinetic knee extension, the excess torque (and work) provided by the acceleration due to gravity is added to the output measured by the dynamometer. However, since some of the potential energy of the limb-lever is expended as KE in response to the force of gravity in eccentric knee extension (as opposed to being generated by the subject during concentric knee extension), attributing all of the work represented by the PE of the system to account for gravity correction is not accurate. Because the amount of work required for this controlled eccentric descent is the potential energy less the kinetic energy (PE - KE), faster motions would require less work to control the system (see Equation 2). When the final KE of the system equals the PE at the start, no muscular work would be needed to intervene and control the descent; in this case, $W_{total} = W_{dyn}$. The final angular velocity at which this occurs, therefore, depends on the moment of the limb-lever system and its potential energy at the start of motion.

Discussion

The isolation of kinetic energy (W_{kin}) as a distinct component of total work (W_{total}) during isokinetics is unique. The present investigation introduced two factors not previously addressed in the assessment of isokinetic work: (a) the role of kinetic energy of the system during eccentric isokinetic bouts, and (b) analysis of the kinetic effects on work measurements within speeds and between genders. The present study contrasted the resulting W_{std} and W_{total} (WMTs) during concentric and eccentric tests. Post-hoc tests were conducted to reveal whether the inclusion of KE in the calculation of W_{total} significantly changed the mean work measurement for individual isokinetic speeds.

In order to relate the error due to ignoring kinetic work, the kinetic error K_{err} was calculated in the present study as W_{kin}/W_{total} (see Table 2). This error factor was significant across speeds and between genders for both concentric and eccentric modes ($p < 0.05$). A parallel finding was reported by Chen et al. (1994) in their analysis of concentric acceleration work. Moreover, the results of the present study indicated that 25 of 28 pair-wise contrasts of errors between concentric speeds were significant ($p < 0.05$); for eccentric data, 13 of 15 contrasts were significant ($p < 0.05$). That comparisons of K_{err} between genders were significant at higher, but not lower, speeds was consistent with the interaction between speed and gender revealed in the ANOVAs. Such comparisons were not reported by Chen et al. (1994).

Although the definition of W_{kin} in the present study differed from the acceleration work in the study by Chen et al. (1994), both encompassed measures of work accomplished outside isokinetic conditions. As presented by Chen et al. (1994), it is evident that the work done during acceleration of the limb-lever system up to a preset isokinetic velocity must also include the portion of work done with respect to gravity during that period. In the present study, the latter work was not isolated for the purposes of defining acceleration work; rather, this portion of work was represented in the potential energy term in the calculation for W_{total} which included work against gravity throughout the entire ROM.

The present study accounted for the change in the moment of inertia with increments in lever arm length. The overall range of the moment of inertia for the Biodex lever arm input device used in this study was 0.178 to 0.285 $kg \cdot m^2$ (lever arm length positions 11.5 to 15 inches). Chen et al. (1994) reported a Cybex II lever arm moment of inertia of 0.162 $kg \cdot m^2$ which estimated using a model of regular shapes such as rectangular rods and cylindrical rods. However, no detail was given to indicate whether changes in lever arm length per participant were considered. Because the dimensions of these attachments vary across manufacturer, the differences in the ranges of possible moments of inertia may affect the amount of work necessary to accelerate them.

A final consideration in the calculation of W_{total} is the method used for estimating the limb segment parameters in determining W_{kin} and the potential energy. The present study employed regression equations based on cadaveric data proposed by Yeadon and Morlock (1989) which should be valid for different populations as long as segmental mass distributions are similar. By comparison, Chen et al. (1994) utilized what was referred to as transverse centriodal moment of inertia values. The segmental centers of mass were also derived from different sources. Whereas the present study used the data provided by Plagenhoef et al. (1983), the comparison study referred to data from another source (Miller and Nelson, 1976). The lack of published evidence regarding error from excluding kinetic energy in the calculation of eccentric total work leaves knowledge about this component of muscle action incomplete.

The calculation of total work during the entire ROM makes the present study unique in light of recent investigations into rate of velocity development, load range, and expression of power. Load range as been shown to decrease as concentric knee extension velocity increases by as little as 3.9% at 60 degrees/sec and as much as 78% at 450 degrees/sec in males (Brown et al. 1995). In the same study females exhibited a decrease in load range from 95.9% at 60 deg/sec to 0% at 450 deg/sec. Taylor et al. (1991) found a decrease in load range from 64.6 degrees at 240 deg/sec to 27 at 400 deg/sec concentrically. As well, Wilk et al., (1994) found a decrease in torque range from 87% at 180 deg/sec to 19% at 450 deg/sec concentrially. Although concentric work was not a focus of either of these investigations, the degree to which load range has been shown to decrease, and oppositely the degree to which ROM during RVD increases at velocities used in the present study and beyond, exemplify the potential degree to which kinetic error would increase under these same conditions. The elucidation of such measurement errors during the acceleration phases associated with isokinetic dynamometry is further evidence that traditional measurements of isometric work are incomplete.

Conclusion

Accounting for the work with respect to the inertial properties of the limb-lever system during concentric and eccentric isokinetic knee extension may introduce significant differences in measurement beyond standard work values. The inclusion of kinetic energy in this investigation introduced a measurement error (K_{err}) which affected calculations of total work: W_{total} is less during eccentric and greater during concentric actions compared to standard, gravity-corrected work measurements (W_{std}). Because of the differential relationship between the work with respect to gravity and kinetic energy as identified in this study, typical standard gravity correction methods applied during eccentric conditions may overestimate the effect of gravity on the limb-lever system, especially at higher angular velocities.

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Key points

- Total isokinetic work is underestimated by standard gravity corrected techniques.
- Standard gravity corrected work measurements overestimate isometric eccentric total work.
- The overestimation of isometric eccentric total work increases with greater angular velocity.

AUTHORS BIOGRAPHY

Brian BOGGESS

Employment

The State of California Department of Corrections providing employment physical testing and evaluation.

Degree

MA

E-mail: brian.boggess@cdcr.ca.gov

Jeff MOFFIT

Employment

A faculty member and chair of the Department of Physical Education and Kinesiology at California State University, Bakersfield.

Degree

EdD

E-mail: jmoffit@csub.edu

Jacobo MORALES

Employment

A faculty member of the Department of Kinesiology at California State University, Fresno.

Degree

PhD

E-mail: jacobom@csufresno.edu

Tim ANDERSON

Employment

A faculty member of the Department of Kinesiology at California State University, Fresno.

Degree

EdD

E-mail: tima@csufresno.ed

✉ **Jeff Moffit**

Department of Physical Education and Kinesiology, California State University, Bakersfield, 9001 Stockdale Hwy, Bakersfield, CA 93311, USA