The effect of isokinetic dynamometer deceleration phase on maximum ankle joint range of motion and plantar flexor mechanical properties tested at different angular velocities

Running Head: Isokinetic isoinertial effects on maximum range of motion

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ABSTRACT

During range of motion (max-ROM) tests performed on an isokinetic dynamometer, the mechanical delay between the button press (by the participant to signal their max-ROM) and the stopping of joint rotation resulting from system inertia induces errors in both max-ROM and maximum passive joint moment. The present study aimed to quantify these errors by comparing data when max-ROM was obtained from the joint position data, as usual (max-ROM$_{POS}$), to data where max-ROM was defined as the first point of dynamometer arm deceleration (max-ROM$_{ACC}$). Fifteen participants performed isokinetic ankle joint max-ROM tests at 5, 30 and 60°·s^{-1}. Max-ROM, peak passive joint moment, end-range musculo-articular (MAC) stiffness and area under the joint moment-position curve were calculated. Greater max-ROM was observed in max-ROM$_{POS}$ than max-ROM$_{ACC}$ ($P<0.01$) at 5 (0.2±0.15%), 30 (1.8±1.0%) and 60°·s^{-1} (5.9±2.3%), with the greatest error at the fastest velocity. Peak passive moment was greater and end-range MAC stiffness lower in max-ROM$_{POS}$ than in max-ROM$_{ACC}$ only at 60°·s^{-1} ($P<0.01$), whilst greater elastic energy storage was found at all velocities. Max-ROM and peak passive moment are affected by the delay between button press and eventual stopping of joint rotation in an angular velocity-dependent manner. This affects other variables calculated from the data. When high data accuracy is required, especially at fast joint rotation velocities (≥30°·s^{-1}), max-ROM (and associated measures calculated from joint moment data) should be taken at the point of first change in acceleration rather than at the dynamometer's ultimate joint position.

Key words: muscle stretching; flexibility; muscle stiffness; velocity-dependent

INTRODUCTION

Maximal joint range of motion (max-ROM) and resistance to tissue elongation (components of 'flexibility') are important physical attributes influencing performances in athletic tasks and activities of daily living (Fong et al., 2011; Hemmerich et al., 2006) and have been linked to musculotendinous strain injury risk (Watsford et al., 2010; Witvrouw et al., 2003).

Max-ROM tests are typically performed by rotating a joint either manually or with external robotic/computerized machinery assistance, e.g. through the use of isokinetic dynamometers (McNair et al., 2002; Palmer et al., 2017). When using isokinetic dynamometers, subjects stop the stretch by pushing a hand-held button at the point of maximal tolerable stretch. However, both electronic and mechanical delays are present between the button push and the stopping of the dynamometer's rotating arm. The latter delay is characterised by the deceleration of the moving lever arm (Brown et al., 1995) leading to an angular velocity-dependent overestimation of max-ROM, although the magnitude of this delay is presently unclear. Since tissues crossing the joint are viscoelastic (i.e. there is a stretch velocity-dependent response; McNair et al., 2002; Rehorn et al., 2014), the maximum moment obtained at stretch termination may also be incorrect because stiffness should be reduced as the tissue stretch speed is decreased upon deceleration of the dynamometer arm. This deceleration would hence complicate the calculation of other variables such as musculo-articular complex stiffness and elastic energy storage, which require the input of both joint moment and joint angular change information (McNair and Portero, 2005). Because of these errors, incorrect conclusions could be made if such variables were compared between tests at different angular velocities and/or in response to physical training, detraining or neurological disorders where tissue mechanical properties are altered. Alternatively, using the max-ROM achieved at the start of the deceleration phase (i.e. true volitional stretch limit) should mitigate these errors.

The purposes of the present study were to i) determine whether max-ROM measured prior to dynamometer arm deceleration is different to the max-ROM determined at the greatest absolute joint position achieved, and whether this difference varies with rotation velocity, and ii) quantify the error introduced into variables calculated from max-ROM and joint moment data (e.g. peak passive joint moment [stretch tolerance], passive end-range musculo-articular stiffness and passive elastic energy storage).

METHODS

Overview and participants

Fifteen active men (27.6±6.9 y, 78.3±11.8 kg, and 1.76±0.06 m) with a minimum 20° dorsiflexion max-ROM during a slow ankle stretch (i.e. $5°·s^{-1}$) with the knee fully extended volunteered for the present study, which was approved by the institutional research ethical committee (project nº 19683). Participants visited the laboratory on three occasions separated by ≥72 h. The first and second visits were devoted to extensive familiarisation of the test procedures (see Supplementary Material 1), and the experimental protocol was performed on the third visit.

Maximum joint range of motion assessment

Participants were positioned on the chair of an isokinetic dynamometer (Biodex System 4, Biodex Medical Systems, Shirley, New York) with the hip angle at 55° (i.e. semi-reclined), knee fully extended (0°), the ankle in the anatomical position (0°; sole of the foot perpendicular to the shank) and the lateral malleolus aligned to the dynamometer's axis of rotation (Kay and Blazevich, 2009). A rigid clip strap was tightened across the foot to minimise heel displacement from the dynamometer footplate. The knee was placed in an extended position to take up slack from the dynamometer system as well as to ensure the plantar flexor muscles were fully stretched during the stretch tests (Blazevich et al., 2012). Thereafter, the participant's ankle was rotated into dorsiflexion from 20° of plantar flexion to full volitional dorsiflexion ROM (point discomfort that they could no longer tolerate stretching), with the stretch terminated when the participant pressed a dynamometer control button. Maximal dorsiflexion range of motion was calculated from anatomical position (0° dorsiflexion). This test was chosen in opposition to active ROM tests (e.g. active dorsiflexion to max-ROM) in order to test the person's maximal stretching ability (i.e. maximum volitional ROM) which is not influenced by the individual's ability to volitionally rotate the ankle into dorsiflexion.

During the stretches, participants were asked to completely relax their muscles whilst muscle activity (EMG) feedback was given instantaneously on a screen placed in front of them. Stretches were performed at three different angular velocities (5, 30, and $60°·s^{-1}$) separated by 90 s. Within each 90-s period, participants performed a 5-s sub-maximal contraction at 60% of MVIC in order to condition the muscle-tendon complex for further strain. Two to five max-ROM trials at each velocity were given with a 1-min inter-trial interval. The number of trials was determined by the max-ROM difference between trials; that is, an additional trial was performed only if a difference ≥5% of max-ROM was observed. Angular velocities were always presented in the order 5, 30, and $60°·s^{-1}$ because the rate of decrease in stiffness across repeated stretches has been reported to be greater when fast stretching angular velocities are imposed (McNair et al., 2002).

Joint position (ϑ), joint moment (τ), joint angular velocity (ω) and joint acceleration (α)

Passive joint moment, joint position, and joint angular velocity were recorded from the dynamometer, and joint acceleration was subsequently derived from the velocity data. The start of stretch was determined *post-hoc* as the last peak of signal deflection that was greater or equal to two standard deviations of the average, unfiltered velocity baseline, i.e. true data prior to stretch. Maximum joint ROM (max-ROM), however, was defined as a) the maximal position observed in the joint position trace (max-ROM$_{POS}$), and b) the position at which the acceleration signal crossed zero and did not return to baseline at the end of the constant-velocity phase (max-ROM$_{ACC}$), which was assumed to be indicative of the participant's button push time, i.e. true volitional max-ROM (see Figure 1).

Passive joint moment and velocity signals were filtered using 15- and 10-Hz low-pass filters, respectively, determined by residual analysis. A Fast Fourier Transformation (FFT) analysis was performed on the position signal to determine the optimal cut-off frequency, which was given by a linear fit of the tail amplitude-frequency relationship. The line that would have crossed the x-axis (had it continued) was considered the optimum cut-off frequency (mean f_c = 35 Hz).

*****place Figure 1 here*****

Peak passive joint moment, end-range musculo-articular complex (MAC) stiffness, and passive elastic energy storage

The passive max-ROM trials enabled max-ROM$_{POS}$, max-ROM$_{ACC}$, peak passive moment (stretch tolerance), the slope of the passive moment curve (end-range MAC stiffness), and the area under the passive moment curve (elastic potential energy storage) to be calculated. Peak passive moment was calculated as the moment at max-ROM$_{POS}$ and max-ROM$_{ACC}$, whereas passive elastic energy was calculated as the area under the passive moment-angle curve from the anatomical position to max-ROM$_{POS}$ and ROM$_{ACC}$ ($Nm\cdot°^{-1}$). The slope of the passive moment-angle curve was calculated as the change in ankle moment per change in joint angle through the last 10° of dorsiflexion (Kay et al., 2016).

Statistical analysis

Descriptive data are shown as mean ± standard deviation (mean ± SD), and the normality of all values was verified with Shapiro-Wilk test. For normally distributed data, paired-samples t-tests were used, whilst data without normal distribution were compared using the Wilcoxon signed-rank test. When a significant difference was observed, Hedge's effect size was calculated as $\frac{Mean2-Mean1}{SD_{pooled}}$ for parametric data (Nakagawa and Cuthill, 2007), whilst $\frac{2r_{pb}}{\sqrt{(1-r_{pb}^2)}}$ was used for non-parametric data;

point-biseral correlation r_{pb} was given by $\frac{z}{\sqrt{N}}$, where *z* is the Wilcoxon Z score and *N* is the sample size (Ivarsson et al., 2013). All data were analysed using SPSS statistical software (version 25.0; SPSS, Chicago, IL, USA) with a level of significance set *a priori* at $\alpha=0.05$.

RESULTS

Maximum joint range of motion

As shown in Figure 2, at $5°\cdot s^{-1}$ a small but significant difference between max-ROM$_{POS}$ (34.9±6.3°) and max-ROM$_{ACC}$ (34.8±6.3°) was observed (t=5.84, *P*<0.001, ES=0.01). Max-ROM determined at angular velocities of 30 and $60°\cdot s^{-1}$ were not normally distributed (*P*<0.05) and were thus compared using Wilcoxon signed-rank tests. Statistical analysis revealed significantly greater max-ROM$_{POS}$ compared to max-ROM$_{ACC}$ in tests performed at $30°\cdot s^{-1}$ (42.8±4.4 vs. 41.9±4.0°; Z=-3.408, *P*=0.001, ES=1.58) and $60°\cdot s^{-1}$ (43.0±5.5 vs. 40.4±4.6°; Z=-3.408, *P*=0.001, ES=1.58). Note that two outliers were observed in the analyses from tests performed at $60°\cdot s^{-1}$ (see Figure 2c) and hence a separate analysis, excluding these participants, was performed. Paired-samples t-tests again revealed significantly greater max-ROM$_{POS}$ than max-ROM$_{ACC}$ (44.8±2.5 vs. 41.9±1.4°; t=8.3, *P*<0.001, ES=1.37). Within-day reliability was determined by standard error of measurement (SEM, i.e. typical error) and coefficient of variation (%). SEM and CV for max-ROM$_{POS}$ were 0.97 and 2.2%, 1.1 and 2.0% and 1.3 and 2.2% for joint rotations performed at 5, 30 and $60°\cdot s^{-1}$, respectively. SEM and CV for max-ROM$_{ACC}$ were 0.98, 2.2%, 0.86 and 1.7% and 1.1 and 2.2% for joint rotations performed at 5, 30 and $60°\cdot s^{-1}$.

Peak passive joint moment (stretch tolerance)

For joint rotations at $60°\cdot s^{-1}$, significantly greater peak passive joint moments values were obtained at max-ROM$_{POS}$ (267.7±73.4 Nm) than max-ROM$_{ACC}$ (257.0±73.0 Nm) (t=4.4, *P*=0.001, ES=0.15). However, no significant differences were observed between max-ROM$_{POS}$ and max-ROM$_{ACC}$ in joint rotations performed at 5 and $30°\cdot s^{-1}$ (*P*>0.2). SEM and CV for peak joint moment obtained from max-ROM$_{POS}$ were 8.2 and 4.8%, 8.2 and 3.0% and 11.4 and 3.8% for joint rotations performed at 5, 30 and $60°\cdot s^{-1}$, respectively. SEM and CV for peak joint moment obtained from max-ROM$_{ACC}$ were 7.9 and 4.6%, 9.8 and 2.9% and 13.5 and 4.4% for joint rotations performed at 5, 30 and $60°\cdot s^{-1}$, respectively.

*****place Figure 2 here*****

End-range musculo-articular complex (MAC) stiffness

Significantly lower end-range MAC stiffness values were calculated using max-ROM$_{POS}$ (4.4±2.4 Nm·°$^{-1}$) than max-ROM$_{ACC}$ (6.2±1.2 Nm·°$^{-1}$) in joint rotations performed at 60°·s^{-1} (t=4.4, *P*=0.004, ES=1.06). However, no significant differences in end-range MAC stiffness values calculated using max-ROM$_{POS}$ and max-ROM$_{ACC}$ were observed for joint rotations performed at 5°·s^{-1} (6.1±2.3 vs. 6.04 ± 2.4, ES= 0.01, *P*=0.2) or 30°·s^{-1} (5.6±2.7 vs. 6.76±1.6, ES= 0.5, *P*=0.06).

Passive elastic energy (area under moment-angle curve)

Significantly greater passive elastic energy values were obtained in max-ROM$_{POS}$ compared to max-ROM$_{ACC}$ for joint rotations at all velocities (49.6±23.8 vs. 49.5±23.8 Nm·°, t=5.95, *P*<0.001, ES=0.01, 5°·s^{-1}; 99.1±37.1 vs. 96.1±33.9 Nm·°, t=2.69, *P*=0.017, ES=0.12, 30°·s^{-1}; 115.8±43.7 vs. 103.2±38.4 Nm·°$^{-1}$, t=6.48, *P*<0.001, ES=0.31, 60°·s^{-1}).

*****Place Figure 3 here*****

DISCUSSION

The maximum ankle joint range of motion (max-ROM) was influenced by the mechanical delay in the stopping of the lever arm of an isokinetic dynamometer, which resulted in an overestimate of the joint angle. Consequently, errors in variables that require the input of max-ROM data (peak passive joint moment, end-range musculo-articular complex (MAC) stiffness and elastic energy storage) were also observed, particularly in joint rotations performed at faster velocities (i.e. ≥30°·s^{-1}).

Max-ROM tests performed in this study required the participant's decision to terminate the stretch at their maximum stretch tolerance by pushing a hand-held button to cease the movement (after which the footplate returned towards plantar flexion). This process is associated with electronic and mechanical delays between the button push and the stopping of the dynamometer's rotating arm. Theoretically, the electronic delay is constant and small irrespective of angular velocity, but the mechanical delay (i.e. deceleration phase prior to stopping of the dynamometer arm) increases linearly with joint rotation velocity (Brown et al., 1995; Nordez et al., 2008). This was experimentally confirmed in the present study to affect max-ROM estimates in joint rotations performed at 30 and 60°·s^{-1}. In fact, the max-ROM determined as the greatest joint angle obtained by inspection of the angle-time data (max-ROM$_{POS}$) was 0.8±0.5° (1.8±1%) and 2.6±1.2° (5.9±2.4%, i.e. ≈ double the within day variability) greater at these velocities than the angle observed when the angular acceleration-time trace deflected downwards (i.e. max-ROM$_{ACC}$). This is considered the point at which the first signal to stop the stretch was received at the dynamometer's motor. However, in joint rotations performed at 5°·s^{-1} the statistically significant 0.1±0.04° (0.2±0.2%) difference was not likely to be practically meaningful. Thus, the acceleration trace should be examined in order to determine the 'true' volitional max-ROM estimates, at least at faster rotation velocities (i.e. ≥$30^\circ\cdot\text{s}^{-1}$). If the acceleration trace is not readily interpretable, mathematical equations are provided in Supplementary Material 2 to estimate max-ROM$_{\text{ACC}}$ from max-ROM$_{\text{POS}}$. It is important to note, however, that although estimates of max-ROM$_{\text{ACC}}$ at 30 and $60^\circ\cdot\text{s}^{-1}$ were accurate, a systematic and potentially meaningful error (-0.4 to 2.8°) in max-ROM estimates was found for joint rotations performed at $60^\circ\cdot\text{s}^{-1}$. Similar results were also observed for peak passive joint moment with errors ranging 6.5–10.6 Nm in joint rotations performed at $60^\circ\cdot\text{s}^{-1}$ (Supplementary Material 2).

In the present study, the maximum passive joint moment (i.e. 'stretch tolerance'; Halbertsma and Goeken, 1994; Kay et al., 2016) obtained at max-ROM$_{\text{POS}}$ was significantly greater than that obtained at max-ROM$_{\text{ACC}}$ in joint rotations performed at $60^\circ\cdot\text{s}^{-1}$, but not at 5 or $30^\circ\cdot\text{s}^{-1}$. The greater peak passive joint moment values obtained in max-ROM$_{\text{POS}}$ in $60^\circ\cdot\text{s}^{-1}$ trials might be related to the additional joint rotation placing further stretch on the musculo-articular complex, which would then produce a greater resistive (i.e. recoil) force. Perhaps surprisingly, the greater (0.1±0.04° and 0.8±0.5°) max-ROMs observed in joint rotations at 5 and $30^\circ\cdot\text{s}^{-1}$ were not associated with a statistical increase in peak passive joint moment. Nonetheless, errors in max-ROM, and thus in peak joint moment, will lead to subsequent errors in end-range MAC stiffness and elastic energy storage calculations. For example, the average end-range MAC stiffness at $5^\circ\cdot\text{s}^{-1}$ was 6.1±2.4 $\text{Nm}\cdot^{\circ-1}$ computed from both max-ROM$_{\text{ACC}}$ and max-ROM$_{\text{POS}}$. However, end-range MAC stiffness computed using max-ROM$_{\text{POS}}$ were 5.6±2.7 and 4.4±2.4 $\text{Nm}\cdot^{\circ-1}$ for joint rotations performed at 30 and $60^\circ\cdot\text{s}^{-1}$, respectively. One might thus conclude that an inverse relationship exists between MAC stiffness and stretching velocity, which is physiologically unreasonable given the viscoelastic properties (rate dependence) of muscle and tendons (Clemmer et al., 2010; Rehorn et al., 2014).

Therefore, the use of max-ROM$_{\text{ACC}}$ is recommended in preference to max-ROM$_{\text{POS}}$ if max-ROM tests are performed at velocities ≥$30^\circ\cdot\text{s}^{-1}$ at the ankle joint.

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CONFLICT OF INTEREST

The authors declare no conflict of interest to disclose.

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