Short communication

Validity and reliability of a new in vivo ankle stiffness measurement device

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Abstract

This investigation was designed to test the validity and reliability of a new measure of inversion/eversion ankle stiffness on a unique medial/lateral swaying cradle device utilizing a test/retest with comparison to a known standard. Ankle stiffness is essential to maintaining joint stability. Most ankle injuries occur via an inversion mechanism. To date, very little information is available regarding stiffness of the evertor muscles in the prevention of excessive inversion joint rotation. Transient oscillation data representing inversion/eversion stiffness was obtained in a bipedal weight-bearing stance with an upright posture. Using commercially available springs with stiffness of 4.80 N/cm the measured value recorded by the cradle was 4.87 N/cm. Mean active stiffness values of the ankle were 35.70 Nm/cm (SD 9.45). The trial-to-trial reliability ICC (2,1) coefficient was 0.96 with an SEM of 2.05 Nm/rad, and the day-to-day reliability ICC (2,k) coefficient was 0.93 and an SEM of 3.00 Nm/rad. The results demonstrate that inversion/eversion ankle stiffness measures on this device are a valid, repeatable and consistent measure. This is relevant because the ability to accurately quantify inversion/eversion ankle stiffness will improve our understanding of biomechanical stability and factors that influence it. It will also enable identification of ankle injury risk factors that will lead to more efficient rehabilitation programs and injury prevention strategies.

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1. Introduction

Ankle sprains are among the most common injury suffered during athletic activities (Garrick and Requa, 1989; Glick et al., 1976). Lack of stability has been theorized to be a primary cause of musculoskeletal injury and research has shown that the active stiffness properties of the musculature are essential to the maintenance of dynamic stability (Duan et al., 1997; Wagner and Blickhan, 1999; Granata et al., 2002; Padua et al., 2005). The bulk of research in ankle stiffness has examined the influence of the triceps surae group during non-weight bearing tasks with a dorsiflexion/plantar flexion motion in the sagittal plane (Allum and Mauritz, 1984; Gottlieb and Agarwal, 1978; Hunter and Kearney, 1982, 1983; Kearney et al., 1997; Kirsch and Kearney, 1997; Mirbagheri et al., 2000; Nielsen et al., 1994; Sinkjaer et al., 1988, 1991, 1993; Toft et al., 1991; Weiss et al., 1986a, b, 1988). A more functional model of ankle stiffness and injury reduction should measure stiffness during a weight-bearing task with an inversion/eversion motion in the frontal plane.

The purpose of this investigation was two fold. First we attempted to validate a new, more functionally accurate method of assessing inversion/eversion ankle stiffness. Second, we assessed the reliability and

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repeatability of the measure on a new, unique medial/lateral swaying cradle device designed and constructed by the researchers to provide and measure transient motion oscillations at the ankle (Fig. 1).

2. Methods

The cradle was designed to allow the subject to maintain a weight bearing, upright stance while perturbing the ankle in an inversion/eversion direction, with the axis of motion aligned with the sub-talar joint, the axis of inversion/eversion (Nordin and Frankel, 2001). A potentiometer was affixed to the axis of rotation to measure the angular displacement during the oscillations. All data were sampled at 1000 Hz.

To assess the validity of the swaying cradle device, we compared the known stiffness of commercially available springs added to the sides of the cradle with the measured value of stiffness obtained from transient oscillations.

To determine the actual stiffness of the commercial springs, we constructed a linear spring-mass oscillator (Fig. 2). One end of each spring was suspended from a steel beam with masses of 1.1 and 2.2 kg attached to the other end. By applying a vertical disturbance the spring-mass system began oscillating. An accelerometer was affixed to the weights to record the motion and obtain the natural frequency and decay of transient oscillations of the springs at the two different mass conditions.

We then conducted transient motion oscillations of the cradle device adding one, two, and three springs to each side of the cradle to measure their stiffness from the device. Transient medial/lateral rotation of the cradle device following controlled perturbation was used to compute stiffness of the springs. The perturbations were performed by dropping a weighted ball through a targeting tube with an electronic trigger for data acquisition onto one of the angled “wings” of the cradle. The contact of the ball caused the transient inversion/eversion oscillations. The energy of the perturbation was held constant by dropping the ball from a height of 100 cm for each perturbation.

Twenty physically active subjects volunteered to participate in the study (Table 1). No subject had a history of recent ankle injury within the previous 8 weeks, had known neuromuscular dysfunction, nor was taking medications influencing neuromuscular performance or response at the time of the study. All subjects signed an informed consent form approved by the University’s Human Investigations Committee before participation in the study.

The leg to be tested was placed with the A/P midline of the heel and the second ray in line with the midline of the cradle. The axis of rotation of the device was aligned with the sub-talar joint of the ankle. The contralateral leg was placed on a stationary support next to and at the same elevation of the platform. The subject’s feet were approximately 30 cm apart. The vertical load applied to the cradle from body weight was recorded by a force plate (Bertec; Columbus, Ohio) and displayed as a percent of body weight. The subjects were instructed to keep 50 percent of body weight on the cradle to maintain an equal bipedal stance.

The perturbations were performed in the same manner as in the validation phase of the study. Subjects were instructed to concentrate on the visual analog

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**Table 1**

<table>
<thead>
<tr>
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<th>Age (yr)</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
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</thead>
<tbody>
<tr>
<td><strong>Males (n = 10)</strong></td>
<td>28.97 (5.66)</td>
<td>177.16 (6.01)</td>
<td>80.79 (13.53)</td>
</tr>
<tr>
<td><strong>Females (n = 10)</strong></td>
<td>25.67 (3.48)</td>
<td>167.15 (5.98)</td>
<td>71.10 (11.87)</td>
</tr>
</tbody>
</table>
display of percent of body weight and to not intervene with the oscillations (Gottleib and Agarwal, 1998). Five perturbations were performed in each testing condition (Fig. 3). Testing conditions consisted of two inertial conditions where external inertia (0.065 and 0.131 kg/cm²) was added through the addition of weights to the sides of the cradle, and one condition without the addition of any external inertia.

In previous studies the ankle inertia was determined using estimates from anthropometric normative data. In our study, we added known amounts of inertia to the system and utilized regression analysis to determine the stiffness of the ankle.

In calculating ankle/cradle inertia versus applied external mass (inertia) we utilized three weight conditions: no added weight, one added weight, and two added weights of equal magnitude (0.57 kg) to each side of the cradle device. Assuming second-order dynamical behavior, the formula

\[ I_{\text{Ext}} = \frac{(k + MgL)}{\omega_n^2} - I_0 \]  

allowed us to plot the added external inertia \( I_{\text{Ext}} \) versus the inverse of the square of the natural frequency \( 1/\omega_n^2 \). It was determined that the pendulum behavior (MgL) had an effect of less than 1% on the ankle stiffness, and was therefore ignored. The stiffness \( k \) was the slope of the regression line and the inertia of the ankle and cradle was the intercept \( I_0 \).

A mathematical model of the data was constructed to accurately compute the frequency \( \omega \) and decay \( \beta \) of the rotational oscillations in the cradle motion. Coefficients \( \omega \) and \( \beta \) were determined from least-means-square fit of the second-order model to the empirical data. To establish reliability or consistency of the subject’s response following perturbation, trial-to-trial and day-to-day variability in stiffness measures were assessed. For ankle stiffness we used a repeated measures (subject by time) ANOVA to analyze subject differences from trial to trial and to calculate intraclass correlation coefficients (ICC 2,1) and (ICC 2,k) as described by Shrout and Fleiss (1979). We also calculated standard errors of measurement (SEMs). Trial-to-trial reliability was determined by comparing the values of all subjects on each trial. Day-to-day reliability was determined by having seven of the subjects return for a second day of testing within 2 weeks of day one. The mean values for each subject from day one and day two were compared.

3. Results

The spring stiffness, confirmed by a simple spring-mass oscillator experiment, resulted in an average value of 4.80 N/cm. By applying the springs to the cradle, the device was utilized to compute stiffness of 4.87 N/cm per spring.

The correlation between the measured transient oscillation data from the cradle and the modeled data yielded an \( R^2 \) (variance of oscillation data attributed to modeled data) of .98 (Fig. 3). In vivo ankle stiffness values were 35.70 ± 9.45 Nm/rad. Excellent trial-to-trial and day-to-day reliability was established. The trial difference \( F_{(1,14)} = 1.299, P = .282 \) and the day-to-day difference \( F_{(1,3)} = 0.145, P = .729 \) were not significant. The ICCs and SEMs for trial-to-trial and day-to-day comparisons were in excess of .93 and 2.05, respectively (Table 2).

![Fig. 3. Comparison of actual data to modeled data.](image)
Table 2
Intra-class correlation (ICC) and standard error of measurement (SEM) to determine trial-to-trial (n = 20) and day-to-day reliability (n = 7)

<table>
<thead>
<tr>
<th></th>
<th>ICC</th>
<th>SEM</th>
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<tbody>
<tr>
<td>Trial to trial</td>
<td>0.96</td>
<td>2.05</td>
</tr>
<tr>
<td>Day to day</td>
<td>0.93</td>
<td>3.00</td>
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4. Discussion

The aim of this study was to test the validity and reliability of a new method for measuring inversion/eversion ankle stiffness in a weight bearing posture. The primary findings of our study suggest that the use of a medial/lateral swaying cradle device provides valid and reliable measurement of ankle stiffness levels.

The comparison of the stiffness results from the linear spring-mass oscillator (4.80 N/cm per spring) to the stiffness results on the swaying cradle device (4.87 N/cm per spring), demonstrates that the device accurately measured spring stiffness. The spring-mass oscillator was a linear measure of stiffness, and the cradle device measured rotational stiffness; however, the angles of displacement on the cradle were small (±5°), so conversion from rotational to linear stiffness is valid.

To get an accurate representation of the measurement reliability, we attempted to separate the repeatability of the ankle cradle device and the stability of the measure. In order to test the repeatability of the instrument we compared the stiffness values obtained over five separate trials within the same treatment session. While typical physiologic responses such as muscular stiffness contain inherent variability, we assumed that the true stiffness values would remain consistent throughout each individual testing session.

Our high ICC value for instrument repeatability indicates that the between subject variance (η² = .97), or subject heterogeneity was very high and the variability across trials (η² = .004) and the error term (η² = .03) were very low. These all suggest that the cradle provides a very consistent measure of inversion/eversion ankle stiffness.

To examine the stability of the measure or its performance consistency across time we asked seven subjects to return to the laboratory for a second measurement within 2 weeks of the initial testing. When using intra-class correlations to assess measurement stability the value of the ICC is inversely proportional to the amount of time between tests (Shrout and Fleiss, 1979). Our very high ICC levels indicate that the 2-week window was sufficient to assess measurement stability. Human performance is variable and it is unlikely that the responses would be identical across trials from day-to-day, so we used the ensemble average of five trials on day 1 and five trials on day 2 to obtain a more general representation of the subject’s performance on the measure. The very high ICC value suggests that the measure of inversion/eversion ankle stiffness is a very stable measure across time.

Evidence from this study indicates that this new method of assessing ankle stiffness in the inversion/eversion direction is both valid and reliable. This new device has the ability to measure ankle stiffness in a weight bearing, upright stance while perturbing the ankle in an inversion/eversion direction, a method that more closely resembles injury models. The ability to accurately and reliably quantify inversion/eversion ankle stiffness will improve our understanding of biomechanical stability of the ankle and factors that influence it.

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References


