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Trunk stiffness and dynamics during active extension exertions

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Abstract

Spinal stability is related to the recruitment and control of active muscle stiffness. Stochastic system identification techniques were used to calculate the effective stiffness and dynamics of the trunk during active trunk extension exertions. Twenty-one healthy adult subjects (10 males, 11 females) wore a harness with a cable attached to a servomotor such that isotonic flexion preloads of 100, 135, and 170 N were applied at the T10 level of the trunk. A pseudorandom stochastic force sequence (bandwidth 0–10 Hz, amplitude ± 30 N) was superimposed on the preload causing small amplitude trunk movements. Nonparametric impulse response functions of trunk dynamics were computed and revealed that the system exhibited underdamped second-order behavior. Second-order trunk dynamics were determined by calculating the best least-squares fit to the IRF. The quality of the model was quantified by comparing estimated and observed displacement variance accounted for (VAF), and quality of the second-order fits was calculated as a percentage and referred to as fit accuracy. Mean VAF and fit accuracy were $87.8 \pm 4.0\%$ and $96.0 \pm 4.3\%$; respectively, indicating that the model accurately represented active trunk kinematic response. The accuracy of the kinematic representation was not influenced by preload or gender. Mean effective stiffness was 2.78 ± 0.96 N/mm and increased significantly with preload ($p < 0.001$), but did not vary with gender ($p = 0.425$). Mean effective damping was 314 ± 72 N s/m and effective trunk mass was 37.0 ± 9.3 kg. We conclude that stochastic system identification techniques should be used to calculate effective trunk stiffness and dynamics.

Keywords

Low back; Dynamics; Stiffness; Model

1. Introduction

Recruitment and control of active muscle stiffness contributes to spinal stability (Bergmark, 1989; Gardner-Morse et al., 1995). Stiffness of the trunk may be defined as the dynamic relation between a small perturbation force and the subsequent trunk displacement. Musculoskeletal joint dynamics are generally nonlinear. However, for small force or angular perturbations about a prescribed operating point (approximately constant trunk moment and posture) the system dynamics can be adequately represented by a linear second-order model (Kearney and Hunter, 1990). Small angular or force perturbations about various levels of mean joint torque have been utilized to calculate the joint stiffness and dynamics in the ankle (Hunter and Kearney, 1982; Agarwal and Gottlieb, 1977), elbow (Zhang and Rymer, 1997), and the knee (Granata et al., 2002). Each of these studies obtained accurate results using a linear second-order model and found that stiffness increases with increased active joint torque. Research concludes that the apparent stiffness of a joint contains both intrinsic components and reflexive components

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(Nichols and Houk, 1976). Paraspinal muscle reflexes contribute to spinal stability by responding to perturbation movements and associated muscle strain with proportional muscle activation (Granata et al., 2004). This proportional reflex response contributes to the overall stiffness of the joint and the combined behavior of the intrinsic muscle stiffness and the reflex response can be referred to as the “effective stiffness” (Cholewicki et al., 2000).

Measurements of trunk stiffness have been reported using diverse experimental methods. The passive stiffness of the trunk has been estimated in anesthetized subjects (Scholten and Veldhuizen, 1986), and in subjects trained to fully relax their trunk musculature (McGill et al., 1994). Considering that the major contributing factor to spinal stability is the recruitment and neuromuscular control of active muscle stiffness, research is necessary to investigate the stiffness of the trunk during active exertions. Active trunk dynamics have previously been investigated by applying either transient (Cholewicki et al., 2000; Bull Andersen et al., 2004) or sinusoidal (Gardner-Morse and Stokes, 2001) force inputs to the trunk and fitting a second-order model to the resulting kinematic data. Cholewicki (2000) utilized a sudden resisted-force release input, while Bull Andersen (2004) used a rapidly applied load. However, since there was a large step change in trunk moment, equilibrium was different before and after the disturbance making it difficult to differentiate between the effects of the neuromuscular change from one equilibrium condition to another versus that of effective stiffness and damping. Specifically, linear second-order estimates of trunk dynamics and stiffness are applicable only for small displacements about a prescribed operating point, i.e. equilibrium must be similar before and after the perturbation. Gardner-Morse and Stokes (2001) maintained trunk equilibrium by applying single-period, 4 Hz sinusoidal force perturbations, but the short period of time used for estimation proved insufficient to measure trunk damping; thus it was neglected. In addition, since only one input driving frequency was investigated, these results may only be valid within a very small frequency range around 4 Hz. Although each of these studies found that trunk stiffness increases with preload, the estimated values of trunk stiffness from each were dramatically different when adjusted for differences in baseline experimental conditions such as trunk moment preload, etc. Published studies demonstrate that improved measurements of joint dynamics and stiffness are possible with high-bandwidth, pseudo-random perturbation sequences about a baseline bias torque (Kearney and Hunter, 1990).

These methods can be applied to accurately estimate effective trunk stiffness in a two-step process. First, characterize the nonparametric dynamics of the system in the form of a vector or curve describing the relation between the input force perturbations and resulting displacement. Since this nonparametric curve provides insight into the system structure and order, the second step is to apply an appropriate parametric model to the nonparametric data to estimate system dynamics, i.e. mass, damping, stiffness. This approach also provides a goodness-of-fit measure to estimate the validity of the trunk stiffness values.

The goal of this study was to quantify effective trunk stiffness during active trunk extension exertions. It was hypothesized that by using high-bandwidth pseudorandom force perturbation sequences applied to the trunk that (1) the nonparametric impulse response function (IRF) can accurately describe the dynamics of the trunk, (2) a linear second-order model can accurately fit the system dynamics of the trunk, and (3) effective trunk stiffness will increase with steady-state trunk extension preload.

2. Methods

2.1. Subjects

Twenty-one subjects with no previous history of low back pain participated after signing informed consent approved by the institutional review board at Virginia Tech. Subjects included 10 males (mean age 23.5 ± 3.2 yr; mean height 183.2 ± 8.4 cm; mean weight $83.4 \pm$

12.7 kg) and 12 females (mean age 20.4 ± 1.5 yr; mean height 164.5 ± 7.2 cm; mean weight 57.7 ± 10.2 kg).

2.2. Experimental protocol

Each subject stood upright in a pelvic restraint structure designed to restrict the motion of the lower body (Fig. 1). A harness and cable system attached the subject to a servomotor (Pacific Scientific, Rockford, IL) such that the cable tension applied flexion loads at the T10 level of the trunk. The motor was programmed to provide three levels of isotonic preload, 100, 135, and 170 N. These preloads required paraspinal muscle preactivation to maintain upright equilibrium of the trunk. Left and right rectus abdominus EMG was displayed on an oscilloscope in plain sight of the subject, and subjects were instructed to keep this antagonistic muscle activity to a minimum in order to reduce unnecessary co-contraction. Once this was accomplished, force perturbations of ± 30 N were superimposed on the preload in a binary pseudorandom stochastic fashion (Fig. 2A) with a flat bandwidth from 0 to 10 Hz. Pseudorandom stochastic inputs were chosen to avoid problems with voluntary responses due to predictable stimuli as recommended by Kearney and Hunter (1990). The applied forces were measured by a torque transducer (Omega TQ301 series, 0–45 N m, Stamford, CT) attached to the shaft of the motor and sampled at 1000 Hz. The small amplitude trunk kinematics in response to the perturbation forces were recorded using two OPTOTRAK infrared emitting diodes (Fig. 2B, solid line) (Northern Digital, Waterloo, Ontario, Canada). Sensors were placed using double-sided tape over the subject's spinous processes palpated at S1 and T10, and were recorded at 200 Hz using a 16-channel A/D converter (Northern Digital, Waterloo, Ontario, Canada).

Three perturbation trials of 10 s each were performed at each preload level for a total of nine data trials presented in random order. The force and displacement signals were inspected visually to assure data quality. Twenty-one of the 189 trials collected were thrown out due to sections of missing OPTOTRAK data presumably caused by the subject's clothing or hair blocking the infrared emitting diode. Both force and displacement signals were demeaned and filtered using a 75 Hz, low-pass, seventh-order Butterworth filter using Matlab (The Mathworks, Inc., Natick, MA) to avoid aliasing then sub-sampled at 200 Hz (Bendat and Piersol, 2000). Signal quality was improved by adding white noise with amplitude equal to 30% of one standard deviation of the input trunk force to the input signal in order to decorrelate process noise and data sampling from the input signal (Ljung, 1999).

2.3. Analyses

To quantify trunk stiffness, the nonparametric compliance IRF relating the pseudorandom force input and the T10 displacement was determined. This IRF was computed from the matrix solution relating the force autocorrelation function and the force/displacement cross-correlation function similar to that discussed in Hunter and Kearney (1983).

Calculation of the nonparametric compliance IRF was based on well-known time domain deconvolution techniques, and assumes a linear time-invariant (LTI) system. The output $y(t)$, i.e., trunk displacement, was described by the impulse response function $h(t)$ of the system convolved (notated with $*$) with the applied input trunk force, $x(t)$:

$$y(t) = \int_{T_1}^{T_2} h(\tau) x(t - \tau) d\tau = h(t) * x(t), \quad (1)$$

where $h(\tau)$ may be considered trivial when $\tau < T_1$ and $\tau > T_2$. Eq. (2) may be represented in discrete time by

$$y(i) = \Delta t \sum_{j=M_1}^{M_2} h(j)x(i-j), \quad (2)$$

where the input, $x(i)$, and the output, $y(i)$, are sampled every Δt seconds, $M_1 = T_1/\Delta t$; and $M_2 = T_2/\Delta t$. Using this property, any LTI system can be described in its entirety by its IRF because once $h(t)$ is known, the output of the system can be determined for any input. With some algebraic manipulation, it is easy to express Eq. (2) in terms of the input autocorrelation function, c_{xx} ; and the input/output cross-correlation function, c_{xy} :

$$c_{xy}(k) = \Delta t \sum_{j=M_1}^{M_2} h(j)c_{xx}(k-j). \quad (3)$$

This equation can then be written in matrix form and solved for H to obtain

$$H = \frac{1}{\Delta t} C_{xx}^{-1} C_{xy}, \quad (4)$$

where C_{xy} is an $M_2 - M_1 + 1$ length vector whose i th element is $c_{xy}(M_1 + i - 1)$, C_{xx} is an $M_2 - M_1 + 1$ square matrix whose i, j th element is $c_{xx}(i - j)$; and H is an $M_2 - M_1 + 1$ length vector whose i th element is $h(M_1 + i - 1)$. H will be a vector representing the IRF, i.e. trunk displacement which would occur given a single force impulse.

Quality of the IRF was quantified by comparing displacements predicted by the IRF, $\text{Displacement}_{\text{predicted}}$ (Fig. 2B, dotted line), with measured displacements, $\text{Displacement}_{\text{actual}}$ (Fig. 2B, solid line), in terms of the percentage of variance accounted for (VAF):

$$\text{VAF} = 100 \times \left(1 - \frac{\sum (\text{Displacement}_{\text{actual}} - \text{Displacement}_{\text{predicted}})^2}{\sum (\text{Displacement}_{\text{actual}})^2} \right). \quad (5)$$

Predicted displacement was estimated by convolving the IRF with the measured pseudorandom force sequence. VAF equal to 100% indicates the IRF exactly predicts the measured trunk displacement signal from the input force perturbations.

Inspection of the IRF shapes revealed that the system appeared very similar to a second-order, underdamped system exhibiting one oscillation (Fig. 3A,B). Therefore, the nonparametric IRFs were subsequently parameterized by least-squares fit to a second-order system

$$H(s) = \frac{1}{ms^2 + bs + k}, \quad (6)$$

where m is the effective trunk mass, b is the effective trunk damping, k is the effective trunk stiffness, and s is the Laplace variable. Damping and stiffness are referred to as “effective” because they consist of both intrinsic and reflexive components; mass is referred to as “effective mass” because we are representing the trunk by a single rigid mass and spring. The flexible attachments between vertebrae as well as the effects of the head and arms will cause the effective mass to be somewhat lower than the actual trunk mass. The quality of the second-order fits obtained was calculated as a percentage and referred to as fit accuracy.

2.4. Error analysis

Prior to subject testing, the analysis procedure was validated by using the methods described above to calculate the mass and effective stiffness of a known spring–mass system. In this case, the calculated mass would be the actual mass rather than an effective mass because the system is a single rigid mass and spring system. A spring with stiffness similar to that of the trunk (2.38 N/mm) was attached to the servomotor in series with a mass that ranged from 6.82 kg (15 lb) to 34.09 kg (75 lb). These values of mass were chosen in order to provide a wide range of test masses while approaching the average trunk mass at the upper end. Stochastic force perturbations similar to our protocol were applied and the resulting displacement was measured. The nonparametric IRF was calculated and subsequently fit to a second-order model.

2.5. Statistical analysis

Statistical repeated measures analyses (ANOVA) were performed to determine the effect of preload on the second-order parameters m , b , and k . The independent variable of gender was analyzed as a between-subject variable while preload was analyzed as a within-subject variable. Analyses were performed using commercial statistical software (Statistica 5, Statsoft, Inc., Tulsa, OK) using a significance level of $\alpha < 0.05$ for all tests. Trends in significant variables were investigated using Tukey honest significant difference (HSD) post hoc analyses.

3. Results

An error analysis of the methods used to calculate trunk stiffness was performed on a known spring–mass system consisting of a spring with a stiffness of 2.38 N/mm in series with a mass that ranged from 6.82 kg (15 lb) to 34.09 kg (75 lb). The average error between calculated mass and actual mass was 0.87 ± 0.34 kg and the average error between calculated stiffness and actual stiffness was 0.022 ± 0.011 N/mm. Since these results represent only a 0.92% error in stiffness and a 4.3% error in mass, the analysis methods in this study were considered accurate enough to proceed with subject testing.

The compliance IRFs calculated in this study were able to accurately predict the active trunk kinematic response to random applied trunk forces, as evidenced by the high values of displacement variance accounted for (VAF). VAFs averaged $87.8 \pm 4.0\%$ and were not significantly influenced by preload ($p = 0.370$) or gender ($p = 0.134$) (Table 1A).

Inspection of the IRFs indicated that the dynamics of the trunk disturbed by small random force impulses could be represented by an underdamped second-order system (Fig. 3A,B). It is clear by inspection of the IRFs and the superimposed second-order least-mean-squares fits that a second-order model provides an excellent description of the linear trunk dynamics. This was validated numerically by determining the second-order fit accuracy. Fit accuracy averaged $96.0 \pm 4.3\%$ and was not significantly influenced by preload ($p = 0.333$) or gender ($p = 0.808$) (Table 1B).

The mean value of effective stiffness was 2.78 ± 0.96 N/mm and effective stiffness increased significantly with preload ($p < 0.001$). There was a 52.7% increase in effective stiffness (2.20 to 3.36 N/mm) from the lowest preload level to the highest (Table 2A). Effective stiffness did not vary with gender ($p = 0.425$) and there was no significant gender-by-preload interaction ($p = 0.101$).

The mean effective damping was 314 ± 72 N s/m (Table 2B). Damping increased 24.8% (274 to 342 N s/m) from the lowest level of preload to the highest ($p < 0.001$). There was no significant main effect of gender in damping ($p = 0.360$), and no significant gender-by-preload interaction in damping ($p = 0.285$).

The mean effective trunk mass was 37.0 ± 9.3 kg (Table 2C). Males had a significantly higher effective trunk mass than females ($p < 0.001$), and effective trunk mass did not vary with preload ($p = 0.098$).

4. Discussion

A method of calculating effective trunk stiffness has been implemented, that is robust and accurate. Stochastic force perturbations were applied at the T10 level of the trunk, and linear time-domain deconvolution techniques were used to calculate the nonparametric IRF representing the trunk dynamics. These IRFs were able to predict an average of $87.8 \pm 4.0\%$ of the measured trunk kinematic response to randomly applied forces. A linear second-order model provided a good description of the dynamic relationship between applied trunk force and displacement, and produced an average fit accuracy of $96.0 \pm 4.3\%$ when superimposed on the IRF. In addition, the parameters (i.e., effective mass and effective stiffness) obtained were validated by connecting a known mass and a spring with known stiffness (2.38 N/mm) to the servomotor, and administering the same protocol and analysis methods that we developed for the subjects. Since the error in both stiffness and mass (0.022 N/mm, 0.87 kg) was much lower than the stiffness and mass standard deviations calculated for the subjects (0.96 N/mm, 9.3 kg), these techniques were deemed accurate.

Joint stiffness has been found to increase with increasing muscle activation in the ankle (Agarwal and Gottlieb, 1977; Hunter and Kearney, 1982), elbow (Zhang and Rymer, 1997), and trunk (Cholewicki et al., 2000; Gardner-Morse and Stokes, 2001; Bull Andersen et al., 2004). Therefore, we hypothesized that the method we developed for calculating effective trunk stiffness would show an increase in stiffness with steady-state preload. As expected, effective trunk stiffness increased 52.7% (2.20 to 3.36 N/mm) from the lowest level of preload to the highest.

The mean value of stiffness in this study was 2.78 ± 0.96 N/mm and ranged from 1.30 to 6.06 N/mm in various subjects and preload conditions. Gardner-Morse and Stokes (2001) applied a 4 Hz sinusoidal force disturbance to the trunk and reported much higher trunk stiffness values in the range of 14.5–19.8 N/mm. Some of the discrepancy in stiffness values can be attributed to the lower preloads in the current study. Also, Gardner-Morse and Stokes (2001) neglected damping which, given the extensive set of musculature the trunk possesses, may provide a significant contribution to trunk dynamics. Finally, much of the discrepancy might be attributed to the frequency content of the input waveform which was applied for system identification purposes. Pseudorandom stochastic inputs excite the system with a very broad frequency spectrum, allowing identification techniques to give relevant information within the system's functional frequency range. Sinusoidal inputs contain only a single frequency and thus can only give relevant information within a very specific frequency band that may or may not be encountered in functional situations (Kearney and Hunter, 1990). The average damped natural frequency observed in our study was 1.17 ± 0.26 Hz, and the largest exhibited by any subject was 1.95 Hz. Based on this frequency content, we advise that stiffness analyses of the trunk should apply a continuous frequency spectrum over a minimum range of 0–6 Hz.

Cholewicki (2000) and Bull Andersen (2004) applied transient step inputs of force to the trunk and calculated average effective stiffness values of 785 ± 580 and 297 ± 61 N m/rad, respectively, when compared at equivalent preload levels in the range of 170–190 N. In our analysis we calculated an average linear effective stiffness at the 170 N preload level of 3.36 ± 1.03 N/mm. Since the average distance between S1 and T10 for our subjects was 203 mm, our linear effective stiffness can be converted to a rotational effective stiffness of 253 ± 55 N m/rad. This agrees with the results of Bull Andersen (2004), but both the mean and standard deviation are lower than those of Cholewicki (2000). The step inputs applied to the trunk by

Cholewicki (2000) were much larger than Bull Andersen or the perturbations of the current study which would result in a much larger change in equilibrium. This may illustrate the importance in maintaining an approximately constant equilibrium preload and may demonstrate the advantage of employing techniques which utilize pseudorandom stochastic inputs about a constant preload level.

Effective trunk damping was found to be 314 ± 72 N s/m and to increase 24.8% (274 to 342 N s/m) from the lowest level of preload to the highest (Fig. 5). Cholewicki (2000) reported a mean damping value of 42 ± 64 N m s/rad, and also found damping to increase with increasing preload. Bull Andersen (2004) reported damping values ranging between 9.1 and 35.8 N m s/rad. Conversion of our linear effective trunk damping to rotational effective trunk damping yields an average value of 27.5 ± 9.0 N m s/rad. This agrees well with Bull Andersen, but is lower than Cholewicki (2001). Much like the variance in effective stiffness, the variance in effective damping observed in the Cholewicki study was much higher than Bull Andersen or the present study.

The increase in joint damping with preload has been shown not to be as large as the corresponding increase in joint stiffness. In fact, the increase in joint stiffness tends to match the increase in joint damping in such a way as to maintain a constant damping ratio,

$\zeta = \frac{1}{2} b / \sqrt{mk}$ (Kearney and Hunter, 1990). Calculation of ζ in our study yielded a mean value of 0.512 ± 121 which, as expected, did not vary with preload ($p = 0.788$). Since the trunk demonstrates a damping ratio as high as 0.512, it is clear that damping plays a large role in trunk dynamics. In fact if one were to neglect damping, effective stiffness may be underestimated by 33%.

The average effective trunk mass in our study was 37.0 ± 9.3 kg, and did not vary with the preload. Males (43.7 ± 6.9 kg) exhibited a significantly higher effective trunk mass than females (30.9 ± 6.6 kg). Each subject's effective trunk mass was roughly half of their total body mass, which is to be expected since the trunk loading occurred at T10 close to the trunk center of mass. Gardner-Morse and Stokes (2001) reported a mean effective mass value of 14.1 kg, and their effective mass increased significantly with preload. They attributed these results to the nonrigid mass coupling of the upper body segments. It is well documented that joint inertia or effective mass should remain independent of joint torque (Agarwal and Gottlieb, 1977; Hunter and Kearney, 1982). Our results agree that effective trunk mass should be invariant with preload and also indicate that the effects of the nonrigid mass coupling of the upper body segments are small enough that effective trunk mass should remain close to the mass of the upper body.

The parameters of muscle dynamics are known to vary with the operating point of the joint determined by the mean level of torque, the perturbation amplitude, the mean joint position, and the level of agonist–antagonist co-contraction (Kearney and Hunter, 1990). This is indicative of a nonlinear system, yet we employed a linear model to determine the trunk dynamics. The linear assumption can be made as long as the mean level of torque is held constant and the perturbation amplitude is kept relatively small so as to stay within one particular operating state of the muscles surrounding the joint. Therefore, any comprehensive model of trunk stiffness must account for these nonlinearities using very small amplitude motion and by varying the mean level of muscle torque in small increments that encompass the entire range of muscular contraction levels. Therefore, the trunk dynamics reported in this study are valid only in the range of preload levels that were applied. The results should not be extrapolated to other levels of muscular activation or displacement amplitudes.

Although this method proved capable of accurately measuring the effective stiffness of the trunk within the trunk operating range examined, it is not without limitations. Related to the protocol, 18% of the trials were thrown out due to missing infrared diode data or poor

displacement VAF. Also, the placement of the infrared diodes at S1 and T10 provided only an approximation of the lumbar tissue displacements because the exact distance change between lumbar soft tissues during extension is unknown. Also, by controlling force perturbations it is possible that although the level of force amplitude was closely regulated, these given forces may cause different magnitudes of motion response from subject to subject. This could mean that two subjects were analyzed at two different operating states, which may influence the muscular response and stiffness characteristics. Future studies will minimize these limitations by using stochastic position perturbations instead of force perturbations. This may provide the additional advantage of allowing the separation of effective stiffness into its intrinsic and reflexive components (Kearney et al., 1997). Future studies should also further investigate the effect that gender has on effective trunk stiffness, as well as other variables such as fatigue, perturbation amplitude, prolonged static flexion, and loading direction.

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Fig. 1. Experimental setup. The servomotor applied a flexion preload to the trunk and then superimposed a binary pseudorandom stochastic force sequence. The resulting displacement was measured. Subjects were securely strapped into a rigid structure to isolate movement to the trunk.

Fig. 2.

Applied trunk force (A) and resulting T10 displacement (B) for a male subject with 100 N preload. Both signals were filtered using a 75 Hz, low-pass, seventh-order Butterworth filter in software (Matlab, Natick, MA). The dotted line represents the predicted displacement determined by convolving the calculated IRF with the trunk force sequence applied. The accuracy of the IRF is evident from the displacement variance accounted for (VAF = 93.2%).

Fig. 3.

A,B. Typical IRFs relating trunk displacement to the applied trunk force for two different subjects and the superimposed second-order least-mean-squares fits. This clearly illustrates that a linear second-order model can accurately describe the trunk dynamics. The large variance in effective mass, damping, and stiffness between these two subjects and conditions is evident in the contrast between graphs A and B.

Table 1

Displacement VAF (A) and second-order fit accuracy (B) for each gender and preload condition

	100 N	135 N	170 N	Mean
(A) VAF (%)				
Males	85.6 (4.6)	87.0 (4.8)	88.1 (2.7)	86.9 (4.1)
Females	88.7 (4.6)	87.9 (3.9)	89.2 (2.3)	88.6 (3.7)
Mean	87.2 (4.8)	87.4 (4.3)	88.7 (2.5)	87.8 (4.0)
(B) Fit accuracy (%)				
Males	96.1 (3.8)	96.8 (2.7)	95.9 (3.7)	96.3 (3.3)
Females	96.4 (3.2)	96.8 (2.3)	96.6 (2.2)	96.6 (2.5)
Mean	96.2 (3.4)	96.8 (2.4)	96.2 (2.9)	96.0 (4.3)

Gender and preload did not have an effect on VAF or fit accuracy as there was no significant statistical difference between the values at any of the conditions.

Table 2

Measured effective stiffness (A), effective damping (B), and effective mass (C) for each gender and preload condition

	100 N	135 N	170 N	Mean
(A) Stiffness (N/mm)				
Males	2.20 (0.68)	2.62 (0.72)	3.07 (0.97)	2.63 (0.85)
Females	2.20 (0.61)	2.91 (0.96)	3.62 (1.06)	2.91 (1.05)
Mean	2.20 (0.63) ^A	2.77 (0.85) ^B	3.36 (1.03) ^C	2.78 (0.96)
(B) Damping (N s/m)				
Males	269 (68)	310 (84)	322 (67)	300 (74)
Females	279 (50)	338 (64)	360 (69)	326 (69)
Mean	274 (58) ^A	325 (74) ^B	342 (69) ^B	314 (72)
(C) Mass (kg)				
Males	42.0 (8.1)	45.4 (5.9)	43.7 (6.7)	43.7 (6.9)
Females	28.9 (5.5)	31.5 (6.6)	32.3 (7.6)	30.9 (6.6)
Mean	35.1 (9.5) ^A	38.1 (9.4) ^A	37.7 (9.1) ^A	37.0 (9.3)

There were no main effects for gender or any significant gender-by-preload interactions. Mean values with similar superscripts were not significantly different ($p > 0.05$).