Biomechanics of the Heel-Raise Exercise

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The purpose of this investigation was to determine whether increases in internal (muscular) demand would be proportional to increases in the external demand during heel-raise exercise. Seven male (mean age 74.9 ± 4.8 years) and 9 female (mean age 74.4 ± 5.1 years) older adults performed both double-leg heel raises and single-leg heel raises under 3 loading conditions (no external resistance and +5% and +10% of each participant’s body weight). Kinematic and kinetic dependent variables were calculated using standard inverse-dynamics techniques. The results suggest that although the single-heel raise led to increases in peak net joint moments, power, and mechanical-energy expenditure (MEE), it did so at the expense of range of motion and angular velocity. In addition, increasing the external resistance by 5% of participants’ body weight did not elicit significant changes in either the power or the MEE of the ankle joint. These effects should be considered when prescribing these exercises to older adults.

Key Words: ankle kinetics, weighted vest, calf raise

The strength and power of the ankle plantar-flexor muscles are important modulators of performance during chair rising (Suzuki, Bean, & Fielding, 2001), stair climbing (Suzuki et al.), and walking (McGibbon & Krebs, 1999; Mueller, Minor, Schaff, Strube, & Sahrmann, 1995). Unfortunately, these muscles also demonstrate large decrements in performance with aging, with community-dwelling older adults (mean age 72 years) generating 20–40% less plantar-flexor strength than that of younger adults (mean age 23 years; Thelen, Schultz, Alexander, & Ashton-Miller, 1996). Even when adjusted for muscle cross-sectional area, physical activity, and gender, there appears to be an appreciable (15%) annual decline in plantar-flexor strength (Amara et al., 2003). In light of these findings, it is not

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surprising that older adults living in either congregate housing or skilled nursing facilities find activities that predominantly involve the plantar flexors (such as the bilateral heel raise) difficult to perform (Alexander, Grunawalt, Carlos, & Augustine, 2000).

Fortunately, older adults can increase both torque- and power-producing capabilities of the plantar flexors by as much as 12–24% with training (Ferri et al., 2003). The standing heel raise (also known as the “calf raise”; Figure 1) is a commonly prescribed exercise for improving the strength and power of the ankle plantar flexors. It is a relatively simple movement, requires little to no equipment, and can be performed in the home. Moreover, the postural control required during the heel-raise exercise might improve performance of activities of daily living to a greater degree than machine-based exercise activities do (Morrissey, Harman, & Johnson, 1995).

Figure 1. The doubleHEEL raise performed while the participant is instrumented for biomechanical analysis.
In order to produce increases in strength or power capabilities of these muscles, an incremental overload of the training stimulus is required. This overload can be provided in the form of a weighted vest (Greendale et al., 2000; Shaw & Snow, 1998) or by performing the heel raise on a single limb (the single-heel raise; Figure 2). The form and amount of overload are often chosen for both exercise programs and clinical trials without appreciating the fact that there might be biomechanical differences. These differences in overload might cause an inappropriate (too much or too little) demand on the ankle plantar flexors, resulting in less than optimal results. Proper exercise prescription for seniors requires knowledge of how these different forms of overload affect the kinematics (or motion of the activity) and kinetics (or forces) of the heel-raise exercise. This will enable those who are working with older adults (both researchers and clinicians) to determine which exercise to choose and how much external resistance to apply.

Figure 2. The single-heel raise performed while the participant is instrumented for biomechanical analysis.
The purpose of this investigation was twofold; first, we wanted to quantify the kinematics and kinetics at the ankle during the double-heel raise (DHR) and single-heel raise (SHR). Second, we wanted to determine the effect of incremental increases in resistance on the mechanical demand associated with each exercise. We hypothesized that there would be a linear association between exercise activities and among loading conditions. That is, the increases in internal (muscular) demand at the ankle would be proportional to the increases in external resistance, and the internal demand for the SHR would be twice that of the DHR. Although we believe that most researchers and clinicians would intuitively agree with this hypothesis, it is important to test this assumption in order to safely and effectively prescribe heel-raise exercise for seniors, as well as to design appropriate clinical trials.

Methods

PARTICIPANTS

Seven male (mean age 74.9 ± 4.8 years) and 9 female (mean age 74.4 ± 5.1 years) older adults from the greater Los Angeles area were recruited via media advertisements. Potential participants were selected using a self-administered medical-history form, bone scans of the lumbar spine and dominant hip joint (dual-energy X-ray absorptiometry; DXA, Hologic QDR1500, Waltham, MA), and a “cleared to participate” letter from their personal physicians. Potential participants were excluded if they had current musculoskeletal (e.g., osteoporosis), cardiovascular (e.g., high blood pressure), or neurological disorders (e.g., dementia or uncontrolled seizures). The purpose and methods of the investigation, along with the rights and responsibilities of each participant, were explained to all participants. Written consent to take part in the study was obtained from all participants, and their rights were protected throughout this investigation. The institutional review board of the University of Southern California approved the study protocol.

EXERCISE PROTOCOL

Each participant performed two exercises: DHR (Figure 1) and SHR using his or her dominant leg (Figure 2). Each exercise was performed at the participant’s self-selected speed. For both exercises, participants were instructed to begin with their foot or feet flat on the floor. On commencing the exercise, participants were instructed to “raise up on your toes as high as possible.” After a slight pause at the top position, participants were instructed to slowly lower their heel(s) back to the starting position. For safety reasons, each participant was instructed to place both hands on a safety bar; however, they were instructed not to use it unless they thought they were going to lose their balance. One of the legs of the safety bar was positioned under a force platform to ensure that participants did not use it to assist them in performing the exercise; use of the bar was quantified as an increase in the ground-reaction force greater than 5% of the participant’s body weight. Trials exceeding this threshold were discounted.
A previous investigation (Salem, Wang, Azen, Young, & Greendale, 2001) found a significant increase in plantar-flexion moments of 5.7% with the application of a weighted vest loaded with 5% of the participants’ body weight, but this increase was nonsignificant with a vest weight of 3%. Because incremental increases of 3% body weight do not appear to produce significant changes in internal demands, and little information is available for resistance doses above 5% body weight in this population, each exercise was performed under three loading conditions: with no external resistance (BW) and with 5% (+5% BW) and 10% (+10% BW) of the participants’ body weight using a weighted vest. The order of the exercises was randomized, but the loading conditions were not: For each exercise, the participant always performed the BW first, followed by the +5% BW and concluding with the +10% BW. This was done in order to ensure that each participant could safely perform the movement with a given resistance before adding more. For each exercise and loading condition, participants performed three single-repetition sets, for a total of 18 sets. Between sets, participants rested for 2–3 min.

INSTRUMENTATION

Ground-reaction forces were obtained using force platforms (Model #OR6-6-1, AMTI, Watertown, MA) embedded in the floor. A single platform was used for the SHR, and two platforms (one for each foot) were used for the DHR. Data were recorded at a rate of 1,200 Hz.

Segmental orientations were determined using a six-camera motion-analysis system (Vicon 370, Oxford Metrics, Oxford, UK). An 18-point modified Helen Hayes marker set was used to model the lower extremities as seven rigid body segments (one pelvis, two thighs, two shanks, and two feet) attached by ideal revolute joints (Kadaba, Ramakrishnan, & Wooten, 1990). Marker coordinate data were recorded at 60 Hz and filtered using a Woltring quintic spline with a mean square error of 20 mm.

Biomechanical Calculations

This investigation was limited to the participants’ dominant ankle joint in the sagittal plane. We defined the mediolateral axis such that plantar flexion was positive and dorsiflexion was negative. Segmental velocities and accelerations were calculated as the differentiation and double differentiation, respectively, of the position data. Ankle-joint velocity was determined as the difference between the shank and foot angular velocities. The location and magnitude of the foot center of mass, along with the foot moment of inertia, were obtained from published data (Winter, 1990). The magnitude and point of application of the ground-reaction force were obtained from the force platform.

Four kinematic and three kinetic variables were of interest for this study. The kinematic variables were peak plantar-flexion angle, movement duration, and peak and average joint angular velocity. The kinetic variables were peak net joint
moment, peak net joint-moment power, and mechanical-energy expenditure (or “total work”). The net joint moment at the ankle was calculated as the moment that satisfied the Newton–Euler equations. Net joint-moment power was determined as the scalar product of the net joint moment and angular velocity. Mechanical-energy expenditure (MEE) was the sum of the absolute values of positive and negative work; it was calculated as the integral of the absolute power–time curve (see Figure 3).

**Statistics**

The mean data from each of three trials for each of the dependent variables were used for statistical analyses. Comparisons were made using a two-way ANOVA (Exercise × Load) with repeated measures. When significant interactions existed, post hoc analyses were conducted between loading conditions within a given activity type using a one-way ANOVA and between activity types for a given load using paired t tests. All analyses were conducted on data obtained from each participants’ dominant limb using SPSS® 11.5 for Windows® (SPSS, Chicago).

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**Figure 3.** Representative net joint-power (JP) curve, at the ankle, for a single participant. A positive JP indicates power generation and concentric muscle action. A negative JP indicates power absorption. The absolute values in the areas between the curve and the x-axis indicate mechanical energy expenditure.
Results

KINEMATICS

Kinematic data including average duration of activity, maximum ankle-joint angles, maximum velocities, and average velocities are presented in Table 1. For both exercise activities, participants began in a position of slight dorsiflexion, proceeded into plantar flexion, held the maximum plantar-flexed position, and then returned to a position of slight dorsiflexion.

PEAK ANKLE-JOINT ANGLES

There was a statistically significant main effect for activity type ($p < .001$), a nonsignificant main effect for loading condition ($p = .144$), and a statistically significant interaction between loading condition and activity type ($p = .025$). For the DHR, there were no significant differences between loading conditions ($p = .210$). For the SHR, the +10% BW condition resulted in a 5.9% smaller peak joint angle than did the BW condition ($p = .040$) and a 4.0% smaller peak joint angle than did the +5% BW condition ($p = .012$). The difference between the BW and +5% conditions was not significant ($p = .482$). The participants consistently achieved greater peak plantar-flexion angles during the DHR than during the SHR, and the difference between the two activities progressively increased as the external resis-

Table 1  Joint Kinematics During Double-Heel Raise (DHR) and Single-Heel Raise (SHR), $M$ ($SD$)

<table>
<thead>
<tr>
<th></th>
<th>Resistance</th>
<th>DHR$^a$</th>
<th>SHR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum plantar-flexion angles (°)</td>
<td>BW</td>
<td>29.12 (7.89)</td>
<td>20.38 (4.56)</td>
</tr>
<tr>
<td></td>
<td>+5% BW</td>
<td>29.92 (7.98)</td>
<td>20.00 (4.98)</td>
</tr>
<tr>
<td></td>
<td>+10% BW</td>
<td>30.05 (7.57)</td>
<td>19.24 (4.94)</td>
</tr>
<tr>
<td>Duration of activity (s)</td>
<td>BW</td>
<td>2.05 (0.54)</td>
<td>2.36 (0.57)</td>
</tr>
<tr>
<td></td>
<td>+5% BW</td>
<td>2.00 (0.55)</td>
<td>2.25 (0.47)</td>
</tr>
<tr>
<td></td>
<td>+10% BW</td>
<td>1.94 (0.50)</td>
<td>2.16 (0.45)</td>
</tr>
<tr>
<td>Maximum angular velocity (°/s)</td>
<td>BW$^b$</td>
<td>122.0 (42.4)</td>
<td>95.0 (33.5)</td>
</tr>
<tr>
<td></td>
<td>+5% BW$^b$</td>
<td>125.4 (47.1)</td>
<td>86.8 (28.9)</td>
</tr>
<tr>
<td></td>
<td>+10% BW$^b$</td>
<td>133.2 (45.8)</td>
<td>88.4 (27.5)</td>
</tr>
<tr>
<td>Average angular velocity (°/s)</td>
<td>BW</td>
<td>37.7 (13.4)</td>
<td>28.8 (12.0)</td>
</tr>
<tr>
<td></td>
<td>+5% BW</td>
<td>42.7 (18.4)</td>
<td>28.3 (11.3)</td>
</tr>
<tr>
<td></td>
<td>+10% BW</td>
<td>45.0 (17.9)</td>
<td>28.7 (7.9)</td>
</tr>
</tbody>
</table>

Note. BW = body weight.

$^a$Main effect, activity type ($p < .05$). $^b$Main effect, load ($p < .05$).
tance increased: 42.9% greater during the BW condition, 49.6% greater during the +5% condition, and 56.2% greater during the 10% condition (all $p < .001$).

**DURATION OF ACTIVITY**

Although there was not a main effect for loading condition ($p = .370$), the duration of the SHR was 20.1% longer than that of the DHR ($p = .003$). There was not a statistically significant interaction between loading condition and activity type ($p = .855$).

**ANGULAR VELOCITY**

In regard to maximum angular velocity, there was a main effect for exercise ($p = .001$) and loading condition ($p = .023$) and a significant interaction ($p = .011$). There was an increase in the peak angular velocity with increasing resistance associated with the DHR, although this increase was only significant between the +10% BW condition and the two lighter conditions ($p = .001$). In contrast, there were no significant differences in peak angular velocity for the SHR (all $p > .05$). The participants consistently achieved higher peak angular velocities during the DHR than during the SHR, and the difference between the two activities progressively increased as the external resistance increased: 28.4% higher during the BW condition, 44.5% higher during the +5% condition, and 50.7% higher during the 10% condition (all $p < .007$).

In regard to average angular velocity, there was a main effect for exercise ($p = .002$). The DHR generated a 46.1% greater average angular velocity than did the SHR. There was not a main effect for loading condition ($p = .085$), and there was no significant interaction ($p = .228$).

**KINETICS**

Kinetic data, including peak net joint moment, power, and MEE, are presented in Table 2. Figure 4 illustrates the net joint-moment data from a single representative participant performing both the DHR and the SHR exercises. A characteristic “double peak” is seen with the net joint moment—one at approximately 10% of the movement cycle and the other at approximately 90% of the movement cycle. Joint power was positive at the beginning of the cycle, indicating that the plantar flexors were acting concentrically; the negative joint power at the end of the cycle indicates that the plantar flexors were acting eccentrically. The joint power in the midrange is close to zero—this corresponds to the pause when the maximum plantar-flexion position is held before return to the starting position.

**PEAK ANKLE NET JOINT MOMENT**

There was a main effect for exercise ($p < .001$), a significant main effect for loading condition ($p < .001$), and a significant interaction between exercise type and loading
Table 2  Joint Kinetics During Double-Heel Raise (DHR) and Single-Heel Raise (SHR), M (SD)

<table>
<thead>
<tr>
<th>Joint Kinetics</th>
<th>Resistance(^a)</th>
<th>DHR(^b)</th>
<th>SHR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum plantar-flexion net joint moment (Nm/kg)</td>
<td>BW</td>
<td>0.85 (0.18)</td>
<td>1.50 (0.23)</td>
</tr>
<tr>
<td></td>
<td>+5% BW</td>
<td>0.90 (0.18)</td>
<td>1.57 (0.26)</td>
</tr>
<tr>
<td></td>
<td>+10% BW</td>
<td>0.95 (0.20)</td>
<td>1.65 (0.27)</td>
</tr>
<tr>
<td>Maximum ankle power (W/kg)</td>
<td>BW</td>
<td>1.39 (0.47)</td>
<td>1.92 (0.52)</td>
</tr>
<tr>
<td></td>
<td>+5% BW</td>
<td>1.50 (0.45)</td>
<td>1.98 (0.50)</td>
</tr>
<tr>
<td></td>
<td>+10% BW</td>
<td>1.65 (0.50)</td>
<td>2.15 (0.51)</td>
</tr>
<tr>
<td>Ankle mechanical energy expenditure (J/kg)</td>
<td>BW</td>
<td>0.59 (0.19)</td>
<td>0.82 (0.24)</td>
</tr>
<tr>
<td></td>
<td>+5% BW</td>
<td>0.62 (0.16)</td>
<td>0.83 (0.21)</td>
</tr>
<tr>
<td></td>
<td>+10% BW</td>
<td>0.68 (0.20)</td>
<td>0.91 (0.20)</td>
</tr>
</tbody>
</table>

\(^a\)Main effect, load (p < .05). \(^b\)Main effect, activity type (p < .05).

![Figure 4](image_url)  
Figure 4. Net joint-moment data for a single participant during the heel-raise activities. DHR = double-heel raise; SHR = single-heel raise; BW = body weight, performed with no external resistance. BW +5% performed with a vest weighing 5% of the participant’s BW. BW +10% performed with a vest weighing 10% of the participant’s BW.
condition \((p = .041)\). For both activities, an increase in external resistance always resulted in an increase in the peak net joint moment (all \(p < .001\)), although this increase tended to be greater for the DHR than for the SHR. From the BW condition to the +5% BW condition, the peak moment increased 7.9% for the DHR and 3.1% for the SHR. From the +5% BW to the +10% BW condition, the peak net joint moment increased 5.6% for the DHR and 5.1% for the SHR. The participants consistently produced greater moments during the SHR than during the DHR, but the difference between the two activities progressively decreased as the external resistance increased: 76.5% greater during the BW condition, 74.4% greater during the +5% condition, and 73.7% greater during the 10% condition (all \(p < .001\)).

**PEAK ANKLE NET JOINT MOMENT POWER**

There was a main effect for exercise \((p = .005)\). Across loading conditions, the SHR generated 33.2% greater average peak ankle power than did the DHR. There was a main effect for loading condition \((p = .001)\), with the +5% BW condition generating 5.1% greater average peak power than did the BW condition \((p = .183)\) and the +10% BW condition generating 9.3% greater average peak power than did the +5% BW condition \((p = .001)\). There was not a significant interaction \((p = .927)\).

**MECHANICAL-ENERGY EXPENDITURE**

There was a main effect for exercise \((p = .004)\), with the SHR generating a 35% greater ankle average MEE than did the DHR across loading conditions. Similarly, there was a main effect for loading condition \((p = .019)\). The +5% BW condition generated a 1.8% greater average MEE than did the BW condition \((p = .530)\), and the +10% BW condition generated a 9.8% greater average MEE than did the +5% BW condition \((p = .016)\). There was not a significant interaction \((p = .665)\).

**Discussion**

Increases in external resistance were not met by proportional increases in mechanical demand at the joint level during heel-raise exercises performed by older adults. We attribute these unexpected kinetic results to the kinematic differences associated with the two exercise techniques and three resistance levels. Because these findings are in contrast to the commonly held belief that increases in internal demand will be proportional to increases in external resistance, they need to be appreciated and understood by clinicians and researchers attempting to improve the function of the plantar flexors via this exercise.

Although increasing the resistance by changing from a DHR to a SHR is an effective means of increasing both torque- and power-producing demands on the ankle plantar flexors, it is not without at least two drawbacks. First, older adults in our study achieved lower angular velocities with the SHR. This finding demonstrates the inverse relation between torque and velocity: As torque increases, velocity decreases (and vice versa; Hill, 1938). It also explains why the net joint moment (affected by angular acceleration) and net joint-moment power (the product
of the net joint moment and angular velocity) did not increase proportionally with an increase in demand. Second, the older adults in our study achieved a smaller range of motion with the SHR than with the DHR, resulting in smaller differences in MEE than anticipated. In addition, because strength gains are range-of-motion and velocity specific (Morrissey et al., 1995), these benefits and drawbacks must be weighed before deciding which exercise to prescribe.

In addition, the effect of small, incremental increases (5–10%) in external resistance on the joint kinematics and kinetics was similar for both the SHR and the DHR exercise. The kinematics of both exercises were largely unaffected by the small increases in resistance (only peak angular velocities at the 10% condition were affected) and had a more pronounced effect with SHR. Kinetic differences associated with changes in resistance were also similar between exercise types. Increases in the peak net joint moments produced closely mirrored the increases in external resistance for both exercises (≈5–10%) and were consistent with resistance/peak-moment relations during gait when older adults increased resistance via a weighted vest (Salem et al., 2001). Peak joint power and mechanical energy expenditure increased significantly only when the external resistance was increased to +10% of the participants’ body weight, however. These observations are in general agreement with the qualitative feedback we received from our participants (they felt that +5%BW condition was not distinguishable from the BW condition) and might help explain why clinical trials using small overload magnitudes (3% and 5% BW) did not find significant increases in knee strength or physical performance when participants wore a weighted vest 2 hr a day, 4 days a week, for 27 weeks (Salem et al.).

Maintaining plantar-flexor strength and power is necessary in order to preserve physical function in an older population. Performing the standing heel-raise exercise (and its variants) with a weighted vest might be an ideal exercise to do so because it requires minimal participant travel, equipment, instruction, and supervision. Our results indicate that the overload at the joint level does not mirror the external resistance. Therefore, we recommend incremental increases in the external resistance equaling 10% of the participant’s body weight. In addition, the single-heel raise is an effective means of increasing the demand at the ankle joint without having to increase the external resistance. Nonetheless, this variant should be prescribed only when it does not adversely affect the range-of-motion and velocity requirements of the exercise. It is now necessary to determine how these resistance doses should be incorporated into a periodized strength-training program for older adults.

References


