Effect of Running Speed and Aerobic Dance Jump Height on Vertical Ground Reaction Forces

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Aerobic dance movement sequences are similar to running in repetitive frequency. The purpose of this study was to compare ground reaction force variables in aerobic dance and running. Five female subjects performed 10 trials of five running speeds (2.4–4.0 ± 0.4 m/s) and five heights (0–8 ± 0.2 cm) of front knee lift aerobic dance steps on an AMTI force plate (1000 Hz). First peak impact force, peak loading rate, high-frequency impulse, and 50-ms impulse increased with increased running speed and jumping height. Time to first peak impact force decreased as running speed and jumping height increased. Although first peak impact forces resulting from airborne aerobic dance movements (1.96–2.62 BW) were greater than first peak impact forces in running (1.30–2.01 BW), running compared to aerobic dance resulted in shorter time to first peak impact force and higher values for loading rate, high-frequency impulse, and 50-ms impulse. When compared to aerobic dance, running exhibits smaller peak vertical forces but higher loading rates and vertical impulses.

Running movements are similar in repetitive frequency to the movement sequences found in various types of aerobic dance exercise programs. Although running is not typically viewed as a jumping activity, it does consist of a series of repeated jumps followed by repeated landings. Unfortunately for the participants in repetitive impact-oriented activities such as walking, running, court sports, and aerobic dance, some researchers have attributed some types of trauma and injury to repeated impacts from landing, but no data have yet been published to substantiate this claim (Francis, Francis, & Welshons-Smith, 1985; James, Bates, & Osternig, 1978; Nigg, 1986; Nigg et al., 1984; Radin et al., 1973; Simon, Radin, Paul, & Rose, 1972).

Researchers and clinicians have studied vertical ground reaction forces in an attempt to quantify impact and load upon the human body during running and the relationship of impact or shock to injury. When an athlete is running at 4.5 m/s, vertical impact forces typically reach a peak of 2.0–2.4 BW in 20–30
Vertical Ground Reaction Forces

ms (Cavanagh & Lafortune, 1980; Clarke, Frederick, & Cooper, 1983; Hennig & Lafortune, 1991). Munro, Miller, and Fuglevand (1987) found that peak impact force and loading rate were running speed dependent; peak impact increased from 1.6 BW at 3.0 m/s to 2.3 BW at 5.0 m/s and loading rate increased from 77 BW/s at 3.0 m/s to 113 BW/s at 5.0 m/s. Other authors have also reported that peak impact forces increase with increasing running speed (Frederick & Hagy, 1986; Hamill et al., 1983).

Numerous studies have attempted to quantify ground reaction forces experienced during the landing phase of jumping movements. Lees (1981) observed that landings can be divided into impact absorption (first 150 to 200 ms of stance) and balance phases. Valiant and Cavanagh (1985) found that forefoot landings result in impact peaks of approximately 1.3 BW in 10 ms, attributed to contact of the anterior portion of the foot, followed by heel contact peaks of 4.1 BW in 37 ms. In landing movements peak vertical impact forces increase with increasing height, and time to peak vertical impact force decreases with increasing height (Dufek & Bates, 1990, 1991; McNitt-Gray, 1991).

Very few studies have specifically quantified the ground reaction forces (GRF) in aerobic dance. Francis, Leigh, and Berzins (1988) found peak tibial accelerations of approximately 3 g in less than 45 ms for a single subject performing a hopping-type aerobic dance movement. Ricard and Veatch (1990) compared the vertical ground reaction force variables in a low- and high-impact aerobic dance movement (front knee lift). Peak impact force was significantly lower in the low-impact movement (1.0 BW) than in the high-impact movement (2.0 BW). Significantly lower loading rates were also found in the low- (14.4 BW/s) than in the high- (42.6 BW/s) impact movement.

The effects of running speed upon vertical ground reaction forces and the effects of landing from various heights in jumping upon vertical ground reaction forces have been well documented. Very few researchers have examined the effects of landing in aerobic dance or compared the GRF components resulting from various impact-oriented activities, such as running, to those GRF components associated with aerobic dance movements. The purpose of this study was to compare vertical ground reaction force variables in aerobic dance and running.

Methods

Subjects

Five female subjects experienced in aerobic dance and running volunteered for the study. The mean values for age, height, and mass were 29.2 ± 7.4 years, 1.70 ± 0.02 m, and 55.57 ± 1.87 kg, respectively. In the year previous to the study, each subject had been a regular participant in aerobic dance classes at least three times per week (3.6 ± 1.3) and had run at least two times per week (2.4 ± 0.9) with a pace between 2.8 and 3.6 m/s.

Selection of Running Speeds

Five running speeds were chosen (2.4, 2.8, 3.2, 3.6, and 4.0 m/s). The choice of speed was based upon two criteria: (a) The speeds selected were generally consistent with those used in previous running studies attempting to quantify vertical ground reaction force parameters (Cavanagh & Lafortune, 1980; Clarke
et al., 1983; Frederick & Hagy, 1986; Hamill et al., 1983; Hennig & Lafontune, 1991; Munro et al., 1987), and (b) the speeds selected were representative of a wide range of paces common to runners of various experience and skill levels. It should be noted that the slowest running speed (2.4 m/s) corresponds to an 11:10 min/mile pace and the fastest speed (4.0 m/s) corresponded to a 6:40 min/mile pace.

Selection of Aerobic Dance Step and Jumping Heights

The aerobic dance step selected for analysis was defined by the International Dance Exercise Association (IDEA) as the front knee lift (FKL); the movement selected is common to both low- and high-impact classes. Figure 1 (a and b) represents the FKL movement sequence for high- and low-impact dance. The sequential order of the phases was as follows: (a) stance and set (preparation), (b) pushoff or takeoff (propulsion), (c) toe-up (low impact) or liftoff or airborne (high impact), (d) landing, and (e) stance and set (preparation).

The five jumping heights selected, which represent the change in height of the center of mass, were 0, 2, 4, 6, and 8 cm. The heights chosen were common to dance choreography and consistent with movement patterns necessary to sustain constant beat/minute rhythms in both low- and high-impact aerobic dance classes. Most impact-oriented aerobic dance movements are performed at heights of 4–6 cm. The 8-cm height represents the maximum height that can be attained while still allowing the participant to sustain a typical aerobic dance class beat/minute

![Diagram](image)

Figure 1 — Front knee lift aerobic dance exercise; movements are performed in order from 1 to 5. High-impact front knee lift (HFKL) consists of airborne phase, Sequence 3. Low-impact front knee lift (LFKL).
rhythm. The height of jump associated with the low-impact movement was set at 0 cm; by definition there is no airborne phase in low-impact aerobic dance (landing foot is grounded throughout exercise).

Data Collection

The investigation consisted of two sessions: 1 day of aerobic dance trials and 1 day of running. The sessions were counterbalanced. Each subject performed 10 trials at each condition of speed or height. The participants were given as many practice trials as needed to comply with consistent left foot landing for requirements of speed (running) and height and cadence (aerobic dance). All subjects wore Nike Cross Trainer XC shoes for the aerobic dance and running trials to eliminate differences between shoe types.

An Advanced Mechanical Technology, Inc. (AMTI) forceplate mounted flush with the floor surface was used to collect data for the vertical ground reaction force parameters. Movement pace for the FKL was monitored by visual inspection and metronome. An individual FKL trial consisted of a total of five FKL movement sequences in which the subject contacted the force plate with the left foot; force data were collected during the third (of five) foot contacts. Jumping heights were calculated on-line according to methods used by Komi and Bosco (1978); only those heights within ±0.5 cm of the required height were retained for analysis. Running pace was monitored over a 3-m area by two photocells attached to a digital clock. Change in velocity of the center of gravity in the anterior-posterior direction during force plate contact was calculated by use of a linear impulse-momentum relationship (Munro et al., 1987); only those trials in which the change was within ±0.1 m/s of the specified pace were collected for analysis.

Data Processing

Force data were recorded with a Zenith 248 microcomputer interfaced to the AMTI amplifier by a Data Translation DT2801-A, 12-bit analog to digital converter. For each trial the data were sampled at a rate of 1000 Hz. A sampling time of 3.5 s was used for each aerobic dance trial; a sampling time of 1.0 s was used for each running trial.

The landing phases of the vertical ground reaction curves for running and for high- and low-impact dance movements were analyzed. From each of the vertical ground reaction force curves for FKL jump heights and running speeds the following dependent variables were calculated: first peak impact force, time to first peak impact force, peak loading rate, high-frequency impulse, and 50 ms impulse.

In this study first peak impact force was defined as the first peak (local maximum) in the vertical force-time curve. The high-frequency impulse was calculated with a fast Fourier transform to convert the vertical force from the time domain to the frequency domain. Inverse Fourier transform was then used to return all frequencies greater than 30 Hz. The area of this high-frequency (>30 Hz) portion of the force-time curve was then integrated to obtain the high-frequency impulse (Figure 2). Fifty-millisecond impulse is defined as the area under the force-time curve during the first 50 ms of ground contact (Figure 2).
For each of the dependent variables a 10-trial average of the five running speeds and five jumping heights was computed for each subject. The group mean was calculated from the 10-trial average of each subject. Linear regression was used to describe the relationship between each dependent variable for running speed and aerobic dance jumping height.

Results

The means for each dependent variable by running speed and aerobic dance jumping height are presented in Table 1. Analysis of the linear regression residuals of each dependent variable as a function of aerobic dance jumping height revealed nonlinear trends. The nonlinear trends were attributed to the low-impact aerobic dance jumps. Because the participant does not become airborne in the low-impact movement, the first peak force is smaller and the time to first peak force is delayed. The removal of the low-impact aerobic dance jumps (0 cm) from the regression models resulted in linear trends for the four remaining high-impact aerobic dance jump heights (2.0, 4.0, 6.0, and 8.0 cm). However, the low-impact aerobic dance values were plotted on the regression curves for descriptive purposes.

Typical Force–Time Curves for Front Knee Lifts

Figures 3 and 4 depict examples of force–time curves of the vertical ground reaction forces resulting from the high- and low-impact dance movements, respectively. As shown in Figure 3, the vertical force–time curve for the high-impact
Table 1  Means and Standard Deviations for Impact Force, Loading Rate, and Impulse Variables by Running Speed and Jumping Height

<table>
<thead>
<tr>
<th>Variable</th>
<th>Running speed (m/s)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>Jumping height (cm)</th>
<th></th>
<th></th>
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<th></th>
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</thead>
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<tr>
<td></td>
<td>2.4</td>
<td>2.8</td>
<td>3.2</td>
<td>3.6</td>
<td>4.0</td>
<td>0.0</td>
<td>2.0</td>
<td>4.0</td>
<td>6.0</td>
<td>8.0</td>
</tr>
<tr>
<td>FP (BW) M</td>
<td>1.30</td>
<td>1.48</td>
<td>1.69</td>
<td>1.76</td>
<td>2.01</td>
<td>1.28</td>
<td>1.96</td>
<td>2.17</td>
<td>2.44</td>
<td>2.62</td>
</tr>
<tr>
<td>SD</td>
<td>0.34</td>
<td>0.35</td>
<td>0.47</td>
<td>0.40</td>
<td>0.41</td>
<td>0.20</td>
<td>0.27</td>
<td>0.41</td>
<td>0.38</td>
<td>0.47</td>
</tr>
<tr>
<td>TFP (ms) M</td>
<td>38.82</td>
<td>40.28</td>
<td>32.08</td>
<td>30.98</td>
<td>30.02</td>
<td>276.02</td>
<td>134.22</td>
<td>121.64</td>
<td>117.66</td>
<td>106.34</td>
</tr>
<tr>
<td>SD</td>
<td>10.25</td>
<td>11.96</td>
<td>13.68</td>
<td>7.24</td>
<td>6.95</td>
<td>114.47</td>
<td>14.56</td>
<td>15.72</td>
<td>14.69</td>
<td>14.28</td>
</tr>
<tr>
<td>LR (BW/s) M</td>
<td>65.06</td>
<td>69.36</td>
<td>92.62</td>
<td>99.54</td>
<td>112.55</td>
<td>16.26</td>
<td>32.99</td>
<td>48.22</td>
<td>56.99</td>
<td>73.12</td>
</tr>
<tr>
<td>SD</td>
<td>22.73</td>
<td>23.19</td>
<td>34.69</td>
<td>26.06</td>
<td>29.55</td>
<td>10.83</td>
<td>9.58</td>
<td>25.28</td>
<td>33.39</td>
<td>44.65</td>
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<td>HFI (BW · ms)</td>
<td>17.37</td>
<td>19.40</td>
<td>23.65</td>
<td>25.40</td>
<td>28.00</td>
<td>8.35</td>
<td>12.86</td>
<td>15.97</td>
<td>18.68</td>
<td>21.10</td>
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<tr>
<td>SD</td>
<td>4.33</td>
<td>4.31</td>
<td>5.03</td>
<td>4.44</td>
<td>4.93</td>
<td>2.55</td>
<td>2.41</td>
<td>3.99</td>
<td>5.14</td>
<td>6.35</td>
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<tr>
<td>FMI (BW · ms)</td>
<td>38.64</td>
<td>42.20</td>
<td>54.37</td>
<td>57.55</td>
<td>67.01</td>
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<td>18.83</td>
<td>23.63</td>
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<tr>
<td>SD</td>
<td>11.59</td>
<td>11.98</td>
<td>13.76</td>
<td>10.99</td>
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<td>3.48</td>
<td>3.37</td>
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</tr>
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</table>

Note. FP = first peak impact force; TPF = time to peak impact force; LR = peak loading; HFI = high-frequency impulse; FMI = 50 ms impulse.
FKL consists of a takeoff or propulsion phase, a flight phase (in which the subject is airborne), and a landing phase (in which contact or impact occurs). The vertical force–time curve for the low-impact FKL (Figure 4) consists of propulsion and landing phases.

First Peak Impact Force

First peak impact force values for the FKLs as a function of jumping heights increased from 1.28 BW (0 cm, the low-impact movement) to 2.62 BW (8.0 cm). First peak impact force values for the five running speeds increased from 1.30 BW at the slowest speed of 2.4 m/s to 2.02 BW at 4.0 m/s. The linear regression equations for first peak impact force from high-impact jumping height (2.0–8.0 cm) and running speed are presented in Figure 5. Linear trends were observed for the prediction of first peak impact force from high-impact jumping height and running speed, \( r^2 = 0.99 \) and \( r^2 = 0.98 \), respectively. As shown in Figure 5, a running speed of 4.0 m/s and a jumping height of slightly greater than 2.0 cm would have a comparable first peak impact force of approximately 2 BW. First peak impact force values resulting from jumping heights of 4.0 cm and above were greater than first peak impact force values predicted from all of the running speeds tested.

Time to First Peak Impact Force

As shown in Figure 6, the prediction of time to first peak impact force from high-impact jumping height and running speed accounted for 97% and 80% of the variance, respectively. Time to first peak impact force for the FKLs as function

![Figure 3](typical_high_impact_front_knee_lift_vertical_force-time_curve.png)

Figure 3 — Typical high-impact front knee lift vertical force–time curve. The vertical force–time curves were analyzed from the beginning of the landing phase to the first local minimum following first impact peak.
Figure 4 — Typical low-impact front knee lift vertical force–time curve. The vertical force–time curves were analyzed from the beginning of the landing phase to the first local minimum following first impact peak.

of jumping heights decreased from 276.02 ms (0 cm) to 106.34 ms (8.0 cm). For the low-impact aerobic dance movement, time to first impact peak deviated markedly from the regression line for high-impact FKLs. With the exception of the slowest running speed (2.4 m/s), time to first peak impact force decreased from 40.28 ms at 2.8 m/s to 30.02 ms at 4.0 m/s.

Peak Loading Rate

Peak loading rates for the FKLs as a function of jumping heights increased from 16.26 BW/s to 73.12 BW/s, 0 to 8.0 cm, respectively. Peak loading rates for the five running speeds increased from 65.06 BW/s at a pace of 2.4 m/s to 112.55 BW/s at 4.0 m/s (Table 1). Linear trends were observed for the prediction of peak loading rate from high-impact jumping height and running speed, $r^2 = 0.99$ and $r^2 = 0.96$, respectively, shown in Figure 7. Peak loading rates for all running speeds tested were greater than the peak loading rates observed in aerobic dance jump heights from 0 to 6.0 cm.

Impulse Variables

High-frequency impulse and 50-ms impulse increased with increasing running speed and jumping height (Table 1). Linear trends were observed for the prediction of high-frequency impulse from high-impact jumping height and running speed, $r^2 = 0.99$ and $r^2 = 0.98$, respectively, shown in Figure 8. The prediction of 50-ms impulse from high-impact jumping height and running speed accounted for 99% and 97% of the variance, respectively (Figure 9). Fifty-millisecond and high-frequency impulses were greater in running than aerobic dance FKLs for all running speeds and jumping heights tested.
Figure 5 — Relationship of running speed and jumping height in aerobic dance front knee lift to first peak impact force. Means for height are indicated by the asterisks and running speeds are indicated by open boxes. The mean for 0 cm height or low-impact dance movement was not included in the regression for height.

Discussion

Two factors that describe the load imposed on the human body by an exercise activity are the magnitude of the force and the rate of force application. Impact forces are arbitrarily defined as high-frequency forces where the peak value is reached in less than 50 ms. The reaction time of the neuromuscular system to a stimulus has been reported to vary from 50 to 75 ms (Jones & Watt, 1971; Nigg, 1985). Impact forces can be described as passive and active based upon frequency and time to peak force. Passive impact forces, reaching a peak in less than 50 ms, have been suggested to cause bionegative effects such as microtrauma in muscles, ligaments, and bone (Nigg, Denoth, & Neukomm, 1981). While both the magnitude and rate of force application have been suggested to cause injury, there is no conclusive evidence to confirm these findings.

In the current study, first peak impact forces for aerobic dance jump heights of 4.0 cm and higher resulted in greater impact forces than in running at speeds of 2.4 to 4.0 m/s, suggesting that greater load is imposed on the performer in aerobic dance than in running. In contrast, the remaining descriptors of imposed load (time to first peak force, peak loading rate, high-frequency impulse, and 50-ms impulse) indicated that running imposes a greater load on the performer.
Figure 6 — Relationship of running speed and jumping height in aerobic dance front knee lift to time to first peak impact force. Means for height are indicated by the asterisks and running speeds are indicated by open boxes. The mean for 0 cm height or low-impact dance movement was not included in the regression for height.

than does the FKL aerobic dance movement. Time to first peak impact forces resulting from the five jumping heights all exceeded 100 ms, whereas time to first peak impact forces resulting from the five running speeds were all below 40 ms (Table 1 and Figure 6). Peak loading rate values resulting from running speeds of 3.2–4.0 m/s were greater than peak loading rate values predicted from the five jumping heights. High-frequency impulse values resulting from running speeds of 3.2 m/s and above were greater than high-frequency impulse values predicted from the five jumping heights (Table 1 and Figure 8). The 50-ms impulse values resulting from the five running speeds all exceeded the 50-ms impulse values resulting from aerobic dance (Figure 9). These data would imply that running at speeds of 3.2 m/s or faster would impose a greater load upon the body than performing front knee lifts (FKLs) at jumping heights normally associated with aerobic dance.

In an impact event such as running or jumping, a shock wave due to deceleration of the center of mass is propagated up the body. This shock wave is composed of passive, high-frequency (>30 Hz) and active, low-frequency components. Although some researchers have attempted to determine the effects of various landing strategies upon peak impact force application and attenuation, it is unknown what loads the human body can actually prepare or preprogram
Figure 7 — Relationship of running speed and jumping height in aerobic dance front knee lift to peak loading rate. Means for height are indicated by the asterisks and running speeds are indicated by open boxes. The mean for 0 cm height or low-impact dance movement was not included in the regression for height.

to accommodate (Dufek & Bates, 1990; Lees, 1981; McNitt-Gray, 1991; McNitt-Gray, Barbieri, Anderson, & Irvine, 1991). In running at 3.83 m/s, peak lower leg accelerations are typically 7–8 g with mean frequency components of 20–25 Hz, and peak skull accelerations are 2–3 g with a mean frequency of 3.5 Hz (Shorten, Valiant, & Cooper, 1986; Valiant, 1990). The magnitude and frequency of an impact shock are attenuated by bone and soft tissue between the lower leg and head. In the present study, the 50-ms impulse represents some of the passive, high-frequency load resulting from impact (Figure 2). However, an undetermined portion of this 50-ms impulse is attenuated by muscular preactivation prior to landing. The high-frequency impulse can be used to describe that portion of the force–time curve that may not be attenuated by muscular preactivation (Figure 2). It is possible that the high-frequency impulse is a better descriptor of the passive load applied to the body during an impact event than the 50-ms impulse.

The relative stress placed on the human body by a force may be described by four factors: the magnitude of the force, the rate at which the force is applied, the point of application, and the direction of force application relative to the body configuration of the performer. In future comparisons of load imposed by running and aerobic dance, the point of force application and relative body
configuration of the performer should be quantified. Aerobic dance movements tend to load the forefoot, thus placing stress on different anatomical structures, when compared to running. Aerobic dance participants often report injuries to the forefoot, lower leg, and knee (Garrick & Requa, 1988).

Conclusions

Across the running speeds and jumping heights tested, comparison of the vertical ground reaction force parameters associated with low- and high-impact FKLs to those same parameters associated with running revealed higher first peak impact forces in FKLs. Although landings from high-impact (airborne) front knee lifts result in greater first peak impact force values than running, landings from running result in shorter time to first peak impact force, higher values for peak loading rate, and greater high-frequency and 50-ms impulse values than FKLs in aerobic dance. While these results suggest that aerobic dance may be less stressful than running, there is no conclusive evidence that high-impact forces or high loading rates cause injury.
Figure 9 — Relationship of running speed and jumping height in aerobic dance front knee lift to 50-ms impulse. Means for height are indicated by the asterisks and running speeds are indicated by open boxes. The mean for 0 cm height or low-impact dance movement was not included in the regression for height.

References


