Analysis of Ground Reaction Forces within the Time and Frequency-Domains:
Reassessment of the Effect of Visually Guided Foot Placement.

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Introduction
The use of visual guidance, or targeting, to tread on a force platform while walking has been reported as a potentially confounding factor in gait research (Oggero et al., 1997). While there is evidence that constraining the foot to a specific area within a walkway alters stepping parameters (Hirokawa, 1989) and promotes the use of visual control strategies (Patla et al., 1996), there is little empirical support indicating that targeting impacts on the magnitude or variability of ground reaction force (GRF) parameters (Grabiner et al., 1995; Patla et al., 1989) or plantar foot pressures (Nicholson et al., 1998).

However, studies investigating the effect of targeting have largely focused on evaluating ground reaction forces, or pressures, within the time-domain. Recent evidence suggests that analysis within the frequency-domain may be a more sensitive method for evaluating ground reaction forces (Giakas et al., 1996). The aim of the current study was to investigate the effect of visual targeting on ground reaction forces analysed within both the time and frequency-domains.

Methods
Eleven healthy volunteers (5 male and 6 female), aged between 18 and 34 years, with no clinical signs of abnormal gait, completed two gait conditions; targeting and non-targeting. Both conditions involved walking at a self-selected speed over a 10 metre walkway covered with paper. The paper obscured a 60 x 90 cm Kistler force platform mounted at the midpoint of the walkway. The force plate had a resonant frequency of 500 Hz and a signal to noise ratio of approximately 26 dB, 2400 dB and 240 dB for the ML, V, and AP components, respectively.

Walking conditions differed only by the presence or absence of a 30 x 24 cm target area that was superimposed over the hidden force platform. In accordance with conventional practice, the starting position of each subject was iteratively modified such that their foot arrived at the target without notable alterations occurring in step length (Giakas et al., 1996). ML, V and AP force data were captured after the between-trial walking speed varied by less than 5 percent. Force data were collected for 5 trials within each condition at a sampling rate of 1000 Hz. In addition, a modified version of the foot printing method outlined by Stuberg et al.\textsuperscript{18} was used to obtain a permanent record of each subject’s step length. Trials were discarded and repeated if the entire footstep was not contained within the target area.

Step length was measured directly from the midpoint of successive ink marks using the xy coordinates of a drawing board. Similarly, the distance of each footstep from the target (HTT) was calculated for each condition. A decrease in the standard deviation of HTT was used to indicate the onset of visual control strategy (Lee et al., 1982).

In order to allow comparisons to previous time-domain studies, eight commonly used GRF parameters (\(F_{x1-3}; F_{y1-3}; F_{z1-2}\)) were normalised to body weight and their relative times (\(T_{x1-3}; T_{y1-3}; T_{z1-2}\)) were expressed as percentages of the stance phase (Figure 1).
Additional variables including the stance phase duration, (milliseconds), the horizontal braking and propulsive impulses, $I_{z1}$ and $I_{z2}$ (N s), and the foot-ground vertical impulse, (N s), were also calculated. The vertical impulse was further decomposed into vertical impulses ($I_{y1}$) and ($I_{y2}$) corresponding to the same time period defined by the braking and propulsive impulses in the horizontal force profile (Figure 2).

Frequency analysis was performed on ML, V and AP force data for each trial using a discrete Fourier transformation with a rectangular window. The period for harmonic analysis was limited to the duration of the stance phase without further extrapolation of the signal. The power spectral density (PSD), an estimate of the power contained within a signal, was determined for each ground reaction force component (Figure 3). As outlined by Harris et al. (1996), the highest frequency component contained within 95 percent of the integral of the PSD was chosen as the criterion to represent the upper limit of the frequency band width, or frequency content, of each signal (Figure 3).

Figure 3. Illustration of the frequency-domain analysis (a) Antero-posterior GRF normalised for body weight and shown in the time domain; (b) Frequency-domain representation of the power spectral density of the AP component (fundamental frequency 1.52 Hz). (c) The frequency content was determined by calculating the highest frequency accounting for 95 percent of the integral of the PSD (6.08Hz). Only the first 13 harmonics have been displayed.
Results & Discussion
Subjects employed visual control strategies on approaching the target area (Figure 4). Targeting was primarily manifest as an increase in step length variability of the step onto the target. Despite an increase in step length variability from 2 to 4%, there were no significant differences in any of the 22 conventional time-domain parameters between the targeting and non-targeting conditions.

Figure 4. A graphical illustration of the standard deviation of the heel-to-target (HTT) distance for each step taken by a representative subject. The onset of visual control near the target (denoted by the arrow) is reflected by a reduction in the standard deviation of HTT.

However, as illustrated in table 1, targeting resulted in a statistically significant increase in both the ML ($t_{10} = -4.07, P = 0.002$) and AP ($t_{10} = -2.52, P = 0.030$) components of the ground reaction force when measured within the frequency-domain.

<table>
<thead>
<tr>
<th>GRF Component</th>
<th>Non-target</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>SD</td>
<td>CV</td>
</tr>
<tr>
<td>ML</td>
<td>10.4*</td>
<td>4.5</td>
</tr>
<tr>
<td>V</td>
<td>4.5</td>
<td>0.6</td>
</tr>
<tr>
<td>AP</td>
<td>5.4*</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Table 1: Mean, standard deviation and mean intra-subject coefficient of variation (%) of the frequency content (Hz) of the GRF signals during targeting and non-targeting.* Indicates P<0.05

Consistent with previous studies, visual control strategies employed while walking toward a target can not be detected by traditional time-domain measures (Grabiner et al., 1996; Nicholson et al., 1998). However, this study demonstrates that targeting does have a significant effect on the frequency content of ground reaction forces in the AP and ML planes. Frequency analysis would, therefore, appear to be a more sensitive analytical technique for evaluating variations in GRF associated with challenges to gait. These findings have methodological implications for research in which GRF is used to characterise and assess abnormalities in gait patterns.

References