The effect of surface stiffness on forelimb stiffness in trotting horses

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Introduction

In running gaits, elastic structures within the limbs of mammals act as springs. They stretch during the first half of stance phase, storing strain energy, then recoil during the second half of stance, converting the stored energy to kinetic energy. This mechanism substantially reduces the energetic cost of locomotion (Alexander et al., 1982; Alexander and Vernon, 1975; Biewener, 1998; Ker et al., 1987). The spring-like behaviour of the limb has led to the development of the spring-mass model of animal locomotion. The animal is modelled as a point mass supported by a single massless linear leg spring. This simple model predicts stride parameters in running humans and quadrupeds with relative accuracy (Blickhan, 1989; Farley et al., 1993; McMahon, 1985; McMahon and Cheng, 1990).

The effect of track surface can be represented by a second spring in series with the leg spring. This model predicts that, to maintain a constant peak vertical ground reaction force (GRF), stance duration and vertical displacement of the centre of mass for a given velocity, leg stiffness would have to increase as surface stiffness decreases. This response has been demonstrated in running humans (Ferris et al., 1998). The aim of the present study was to determine whether the same response occurs in ungulates. Forelimb stiffness was measured in horses trotting over a stiff rubber matting surface and a compliant sand surface. It was hypothesised that forelimb stiffness would be greater on sand compared to rubber.

Methods

Five clinically sound horses (body mass: 480–630 kg) were used for the experiment. Prior to data collection, 28 mm diameter circular reflective markers were attached to the right side of each horse over the tuber of the scapular spine, the tuber on the proximal lateral radius and the lateral wall of the right fore hoof. In addition, a 40 mm diameter spherical marker was positioned over the dorsal spinous process of the fourth thoracic vertebra (T4).

The experiment was conducted on a 1.5 m wide by 20 m long outdoor concrete pathway in which a force plate (Model 9287 Kistler Instruments, Switzerland) was embedded 12 m from the start. A two camera 3D optical motion capture system (Proreflex, Qualisys, Sweden) was positioned adjacent to the pathway to record the positions of the reflective markers as the horses passed over the force plate. Data collection from the force plate and motion capture system was synchronised electronically.

A stiff track was constructed by covering the pathway with 10 mm thick rubber matting. The section of matting over the force plate was mechanically isolated from the rest of the track and fixed rigidly to the surface of the force plate. A compliant track was constructed by covering the pathway with sand to a uniform depth of 115 mm. Sufficient water was added evenly over the surface to ensure that the horses did not penetrate through the sand to the concrete base and that the reflective markers on the hoof wall were not obscured by the surface. The moisture content of the sand was approximately 20 % throughout the experiment. The surface was compacted with a roller between horses and levelled with a rake between trials.

The horses were led in trot at constant speed along the tracks. GRF and positional data were recorded at 720 Hz and 240 frames per second respectively. Trials were saved if the right fore hoof landed within the central
region of the force plate. This procedure was repeated until seven trials for each horse on each surface had been collected.

GRF data were used to calculate peak vertical GRF and stance duration. Ground contact and lift-off were detected using a vertical GRF threshold of 100 N. Surface deformation was calculated as the change in vertical height of the hoof marker between ground contact and peak vertical GRF. Surface stiffness was calculated by dividing the increase in vertical GRF, from ground contact to peak force, by surface deformation.

Forelimb length was measured between the scapular spine marker and the hoof marker. Distal forelimb length was measured between the radial tuber marker and the hoof marker. Stiffness of the whole or distal forelimb was calculated by dividing peak vertical GRF by the change in length of the appropriate part of the limb from immediately before ground contact to time of peak GRF.

Subject velocity was calculated using the trajectory of the T4 marker. The effect of surface on all measured parameters was determined by comparing velocity-matched trials using a paired t-test. Throughout, p<0.05 was considered significant.

**Results and Discussion**

Overall, three of the five subjects travelled significantly faster on sand, one was significantly faster on rubber and one showed no significant difference. From these data, seventeen velocity matched pairs of trials were extracted (between two and six for each subject) and used for further analysis. For the velocity matched data, mean velocity for all horses was 3.30 m/s on rubber and 3.31 m/s on sand. Mean surface stiffness was 2704 N/mm for rubber and 319 N/mm for sand. The effects of surface stiffness are summarised in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean for rubber surface</th>
<th>Mean for sand surface</th>
<th>Standard deviation of difference within pairs</th>
<th>2-tailed p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whole forelimb stiffness (N/mm)</td>
<td>50.895</td>
<td>48.969</td>
<td>5.071</td>
<td>0.137</td>
</tr>
<tr>
<td>Distal forelimb stiffness (N/mm)</td>
<td>53.794</td>
<td>54.305</td>
<td>3.000</td>
<td>0.808</td>
</tr>
<tr>
<td>Peak GRF (N/kg)</td>
<td>11.480</td>
<td>10.747</td>
<td>0.524</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Stance duration (s)</td>
<td>0.299</td>
<td>0.309</td>
<td>0.016</td>
<td>0.029</td>
</tr>
</tbody>
</table>

**Table 1.** Effect of surface stiffness on forelimb stiffness and ground reaction force parameters in horses. All comparisons made within pairs of trials matched for subject and velocity.

Forelimb stiffness and distal forelimb stiffness did not increase significantly on sand as hypothesised. Two possible explanations for this are discussed below:

Firstly, the result may have been due to the type of surface used. Ferris et al. (1998) used elastically deforming surfaces, while the sand used in the present study deforms plastically. Zamparo et al. (1992) found that humans maintain the same stride frequency when running on sand or on a firm surface. Based on this result, Ferris et al. (1998) proposed that humans may also adjust leg stiffness to compensate for inelastic compliant surfaces such as sand, but the authors are unaware of any published work that has tested this hypothesis. Further experiments will determine whether horses adjust limb stiffness only in response to changes in the stiffness of elastically deforming surfaces. This seems unlikely, however, as the surfaces that horses (and humans) evolved to move over, and that horses typically move over today, have relatively low elasticity. For example, turf surfaces used in horse racing return only 3.6 % of the energy received during impact (Zebarth and Sheard, 1985).
Secondly, horses may not be capable of adjusting limb stiffness. In humans, the increase in leg stiffness that occurs when hopping on a compliant surface is the result of alterations in ankle stiffness and knee angle at touch down (Farley et al., 1998), presumably through the actions of the relatively large gastrocnemius and quadriceps muscles. In the horse, many of the limb joints are supported by muscle-tendon units that comprise a high proportion of tendinous material and a relatively small muscle belly. Examples include serratus ventralis at the scapulotrunk joint, biceps brachii at the shoulder joint and interosseus and the digital flexor muscles at the metapodialphalangeal joints. The tendinous structures in the limb are referred to collectively as the passive stay apparatus and allow the animal to remain standing for long periods without fatigue. They stretch and recoil during locomotion, providing an estimated recovery of up to 40 % of mechanical work (Biewener, 1998). In the present study, it was particularly notable that almost all shortening of the forelimb (94 % on rubber; 91 % on sand) occurred in the distal part of the limb through hyperextension of the metacarpalphalangeal joint. When the size of the muscles supporting this joint is compared to the major leg muscles in humans, it seems unlikely that horses would be capable of making similar adjustments to limb stiffness.

The effect of a decrease in surface stiffness, without a compensatory increase in limb stiffness, was to significantly decrease peak vertical GRF and increase stance duration. This is the effect predicted by the spring-mass model. Horses and other unguligrade mammals travelling over surfaces of varying stiffness may have to alter locomotor strategy to accommodate such changes. The implications of these alterations for load regulation, susceptibility to injury and the energetic cost of locomotion on different surfaces merit further investigation.

References


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