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Modeling equine race surface vertical mechanical behaviors in a musculoskeletal modeling environment

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ABSTRACT

Race surfaces have been associated with the incidence of racehorse musculoskeletal injury, the leading cause of racehorse attrition. Optimal race surface mechanical behaviors that minimize injury risk are unknown. Computational models are an economical method to determine optimal mechanical behaviors. Previously developed equine musculoskeletal models utilized ground reaction floor models designed to simulate a stiff, smooth floor appropriate for a human gait laboratory. Our objective was to develop a computational race surface model (two force–displacement functions, one linear and one nonlinear) that reproduced experimental race surface mechanical behaviors for incorporation in equine musculoskeletal models. Soil impact tests were simulated in a musculoskeletal modeling environment and compared to experimental force and displacement data collected during initial and repeat impacts at two racetracks with differing race surfaces – (i) dirt and (ii) synthetic. Best-fit model coefficients (7 total) were compared between surface types and initial and repeat impacts using a mixed model ANCOVA. Model simulation results closely matched empirical force, displacement and velocity data (Mean R^2 = 0.930–0.997). Many model coefficients were statistically different between surface types and impacts. Principal component analysis of model coefficients showed systematic differences based on surface type and impact. In the future, the race surface model may be used in conjunction with previously developed the equine musculoskeletal models to understand the effects of race surface mechanical behaviors on limb dynamics, and determine race surface mechanical behaviors that reduce the incidence of racehorse musculoskeletal injury through modulation of limb dynamics.

1. Introduction

Musculoskeletal injury contributes to large attrition within the horse racing industry (Parkin, 2012). Race surface is among the factors that have been implicated in the incidence of musculoskeletal injury (Anthenill et al., 2007; Boden et al., 2007; Cohen et al., 1997; Estberg et al., 1998; Hernandez et al., 2001). Differences in equine fatalities between racecourses prompted studies examining the effect of race surface. One study that examined 115 factors related to racehorses, training, and race conditions found that the track condition was one of nine factors significantly associated with racehorse fatality (Boden et al., 2007). Similarly, another study found that firmer racetrack surfaces increased odds of racehorse fatality (Parkin et al., 2004).

Historically, racetrack surfaces have been developed empirically, largely based on material availability, workability, and compatibility with environmental conditions. Over the past two decades, some traditional dirt or sand surfaces were replaced with synthetic surfaces. Even though musculoskeletal injuries declined with synthetic surface installations (Arthur, 2010), anecdotal complaints of synthetic surfaces including slower race times and increased hindlimb lameness (Steffanus, 2012) contributed to the justification for reconversion of some synthetic surfaces to dirt surfaces.

Racehorses often train and compete at multiple racetracks across different regions, states, and countries within a calendar year. Racehorse musculoskeletal tissues must adapt to each track's unique surface during training and competition to optimize racehorse performance and avoid injury. However, tissue adaptation occurs over periods of weeks or months (Martin, 2007), periods that may exceed

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the length of a race meet at a particular racetrack. Racehorses that are maladapted to environmental loads may be more susceptible to musculoskeletal injury. Thus, a standard for racetrack surface mechanical behavior is needed so that racehorses interact with a narrow range of track mechanical behaviors while training and competing across multiple tracks. A well-chosen standard has the potential to optimize racehorse limb loading for injury prevention. However, the optimal race surface behavior that reduces risk for injury is unknown.

The optimal race surface mechanical behavior should be specified at the track surface, rather than by specifying track material, since the environments of each track will cause the materials to behave differently. Material selection (Setterbo et al., 2013), along with temperature (Peterson et al., 2010), moisture content, and maintenance procedures (Peterson and Mcilwraith, 2008), influence apparent mechanical behavior of the whole surface medium experienced by the horse. Therefore, identical race surface composition and materials installed in two different environments may exhibit different behaviors. Regional racetracks can independently determine the material composition and maintenance procedures needed to achieve a specified, standardized, apparent surface mechanical behavior.

Computational modeling is an economical method to assess a wide range of potential race surface designs, and their effect on equine limb mechanics. Previous studies have quantified limb kinematics in trotting (Chateau et al., 2009; Crevier-Denoix et al., 2009), cantering (Setterbo et al., 2009) and galloping horses (Symons et al., 2014) on different existing surfaces. However, installation of experimental race surfaces is costly, on the order of millions of dollars; and data collection and analyses involving live animals is time-consuming. Previous studies have developed a equine forelimb musculoskeletal models (Harrison et al., 2010; Swanstrom et al., 2005); however, race surface mechanical behavior has not been considered in these models. A computational race surface model used in conjunction with equine musculoskeletal models would be an economical, efficient method to understand the effect of surface on limb dynamics, and reduce the use of live animals in research.

More accurate race surface models are needed to study the interaction between race surface mechanical behaviors and the loading and deformation of musculoskeletal structures within galloping racehorses. Race surface behaviors have been quantified using impact devices designed to replicate the effective mass of a horse's hoof striking a race surface at fast trot or slow gallop (Peterson et al., 2004; Setterbo et al., 2011). The floor force model in musculoskeletal modeling software (Neptune et al., 2000) was designed to simulate stiff laboratory surface mechanics, and is unable to reproduce measured race surface mechanical behaviors. There is a need for a more sophisticated surface model that captures equine race surface behavior and is compatible with SIMM. Vertical peak forces and impulses measured at the hoof during canter are 190% and 305% greater than those in the horizontal direction (Setterbo et al., 2009). Therefore, developing a surface model that describes track surface vertical mechanical behavior would be an important first step to developing a comprehensive surface model for use in equine movement simulations. The objective of the present study was to modify the currently available SIMM race surface force function to enable simulation of experimentally observed race surface vertical mechanical behaviors from two racetracks with different surfaces. Subsequent studies will incorporate horizontal race surface mechanical properties into the model.

2. Methods

The race surface model was developed by augmenting a spring floor function in SIMM (Neptune et al., 2000) that was designed to apply ground reaction forces to human foot models during forward and inverse dynamic simulations. In the spring floor model, simulation points (nodes) are placed at various locations on the musculoskeletal model. When these nodes translate below the plane of the floor, forces are applied at each node, as a function of vertical displacement(z) and velocity($\dot{z}$), to support the model during stance and limit the model from further penetrating the floor. The native spring floor function (single nonlinear function, 5 coefficients) was modified (two serial displacement threshold functions: linear and nonlinear, 7 coefficients including a penetration depth transition between functions) to simulate track surface mechanical data collected in the field using a track-testing device.

2.1. Empirical data

Race surface mechanical behaviors used to develop a modified spring floor function consisted of force and displacement data previously collected and published by our research group (Setterbo et al., 2013). Force and displacement data were recorded (2000 Hz) during vertical impacts of a Track-Testing Device (TTD, Fig. 1) on surfaces of two commercial racetracks with differing race surfaces, one dirt surface (n=92 impacts; 83% sand, 10% silt, 7% clay) and one synthetic surface (n=81 impacts; 80% sand, 20% rubber and fiber). The velocity of the device at impact was determined by differentiating displacement data. Impact testing was performed at three drop heights (i.e. 3 impact velocities) across multiple sites, over four days at each racetrack, to simulate a racehorse's hoof impacting the surface at fast trot or slow gallop (Setterbo et al., 2011). Further, initial and repeat impacts were performed at each location to determine surface behavior of harrowed and consolidated material. TTD axial force (F_z, Fig. 1) was zeroed during freefall. Then, a negative preload was applied during freefall due to a non-zero frictional force ($F_{friction}$) observed within the linear bearings of the TTD. This frictional force was determined by fitting a 2nd order polynomial function to freefall displacement data. This function was then differentiated twice to determine the average acceleration of the TTD during freefall ($\ddot{z}_{1,FF}$). The frictional force (Eq. 1) was calculated as the difference between the observed acceleration during freefall and acceleration due to gravity (g, $-9.81\ \mathrm{m/s^2}$), multiplied by the total moving mass of the TTD (M_1+M_2).

$$F_{friction} = (M_1+M_2)(g-\ddot{z}_{1,FF}) \tag{1}$$

Impact start and end were defined at the bounds of positive force data. Time and displacement data were zeroed at impact start. Forces recorded by the TTD load cell (F_{TTD}) were internal to the device, and less than loads at the device-surface interface (F_{GRF}, Fig. 2). Therefore, ground reaction forces (F_{GRF}, Eq. 2A-B) were calculated as a function of the TTD mass distribution [mass above (M_1) and mass below (M_2) the load sensor], friction force ($F_{friction}$), and recorded forces (F_{TTD}). The two masses were assumed to be rigidly attached, such that displacements z_1 and z_2 were equal (z).

$$F_{\mathrm{GRF}} = \frac{M_2}{M_1}F_{friction}\,sgn(-\dot{z}) + \frac{M_1+M_2}{M_1}F_{\mathrm{TTD}} \tag{2A}$$

$$sgn(z) = \begin{cases} -1 & if\ \ z<0 \\ 0 & if\ \ z=0 \\ 1 & if\ \ z>0 \end{cases} \tag{2B}$$

Fig. 1. Track testing device (TTD) positioned over a synthetic surface.