Comparison of equipment used to measure shear properties in equine arena surfaces

Lewis, Kate, Northrop, Alison J, Crook, Glen Martin, Mather, John, Martin, Jaime H, Holt, Danielle, Clayton, Hilary M, Roepstorff, Lars, Peterson, Michael and Hobbs, Sarah Jane

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Abstract

The design of a novel apparatus, the Glen Withy torque tester (GWTT), for measuring horizontal shear properties in equine sport surfaces is described. Previous research has considered the effect of vertical loading on equine performance and injury but only limited discussion has concerned the grip or horizontal motion of the hoof. The horizontal support of the hoof by the surface must be sufficient to avoid excess slip without overloading the limb. The GWTT measures the torque necessary to twist an artificial hoof that is being pushed into the surface under a consistently applied vertical load. Its output was validated using a steel surface, then was used to test two sand and fibre surfaces (waxed and non-waxed) through rotations of 40-140°, and vertical loads of 156-980 N. An Orono biomechanical surface tester (OBST) measured longitudinal shear and vertical force, whilst a traction tester measured rotational shear after being dropped onto the surfaces. A weak, but significant, linear relationship was found between rotational shear measured using the GWTT and longitudinal shear quantified using the OBST. However, only the GWTT was able to detect significant differences in shear resistance between the surfaces. Future work should continue to investigate the strain rate and non-linear load response of surfaces used in equestrian sports. Measurements should be closely tied to horse biomechanics and should include information on the maintenance condition and surface composition. Both the GWTT and the OBST are necessary to adequately characterise all the important functional properties of equine sport surfaces.

Key Words

Torque; shear; arena surface; slip; grip; footing

Nomenclature

DDFT	Deep digital flexor tendon	
D_{max}	Peak vertical displacement (GWTT)	(mm)
GWTT	Glen Withy torque tester	
$GRFH_{max}$	Peak longitudinal ground reaction force (OBST)	(kN)
$GRFV_{mean}$	Mean vertical ground reaction force (GWTT)	(N)
$GRFV_{max}$	Peak vertical ground reaction force (OBST)	(kN)
OBST	Orono biomechanical surface tester	
SDFT	Superficial digital flexor tendon	

SL	Suspensory ligament	
Slip	Horizontal displacement from impact to $GRFV_{max}$ (OBST) calculated from double integration of *GRFH*	(mm)
T_{max}	Peak torque (GWTT)	(Nm)
T_{maxTT}	Maximum recorded torque (traction tester)	(Nm)

1 Introduction

The loading of surfaces by horse hooves is complex due to both the range of gaits and speeds and the manoeuvres performed by the horse and the diverse characteristics of the different surfaces. The functional properties of racetrack surfaces have been studied extensively (Peterson, Roepstorff, Thomason, Mahaffey, McIlwraith, 2012; Ratzlaff, Hyde, Hutton, Rathgeber, Balch, 1997; Reiser, Peterson, McIlwraith, Woodward, 2000; Setterbo, Fyhrie, Hubbard, Upadhyaya, Stover, 2012) but less is known about the characteristics of arena surfaces that are often used for non-racing equestrian sports which involve a more diverse range of athletic activities and hoof surface interaction patterns. In nearly all cases surfaces used for equestrian sports are both highly non-linear and strain rate dependent. For instance, the surface response when executing a canter pirouette in a dressage competition may be quite different to a quick turn during the jump off of a show jumping competition. As the load on the surface increases the typical riding surface increases in stiffness (Reiser et al., 2000) and, in general, the surface will also become stiffer as the load is applied at a higher rate (Setterbo et al., 2012). Since shear resistance of a surface is directly related to the surface stiffness, the grip characteristics are also expected to change with load and loading rate. Thus, there is a need to understand the responses of arena surfaces to both the speed and magnitude of loading, as the stiffness and shear resistance of the surface will influence both the horse's ability to perform and the risk of it receiving an injury.

Shear resistance relates to the frictional forces that are generated between the hoof and the surface and to friction between the particles within the surface (Hobbs et al., 2014). Linear shear resistance affects sliding of the hoof across the surface in a horizontal plane especially during braking phase of stance in straight-line movement. It also affects resistance of the surface when the hoof is in an angled position relative to the ground, as found during push off and sharp turns. Rotational shear resistance affects rotation of the hoof into the surface material, which is also seen during push off and sharp turns. The sliding of the hoof on the surface can either occur between the shoe and the surface, or within the material beneath the hoof depending on the specific characteristics of the surface and the design of the shoe. In addition, the forces generated by the horse's musculotendinous system tend to rotate the hoof into a toe-down orientation within the surface material as the limb generates propulsion (Thomason & Peterson, 2008). The surface must provide sufficient resistance to the horizontal sliding motion or rotation of the hoof to enable the horse to obtain grip, which prevents slipping, tripping or falling (Murray, Walters, Snart, Dyson, Parkin, 2010a) and provides traction for propulsive effort (Crevier-Denoix et al., 2010). Excessive resistance to the horizontal motion or rotation is expected to result in an earlier onset of hoof braking and an increase in the magnitude of the peak stress and loading rate in the limb (Gustås, Johnston, Drevemo, 2006). Reduced horizontal motion of the hoof has been associated with surface hardness (Wilson & Pardoe, 2001; Orlande, Hobbs, Martin, Owen, Northrop, 2010) and harder surfaces tend to increase the magnitude of higher frequency vibrations during impact and limb loading (Chateau et al., 2009). The high frequency components of the loading are reported to be attenuated mainly by the hoof, and the magnitude of peak stress is gradually damped proximally by the distal limb structures (Lanovaz, Clayton, Watson, 1998; Willemen, Jacobs, Schamhardt, 1999). High frequency loading damages bone and articular cartilage predisposing to the development of osteoarthritis (Folman, Wosk, Voloshin, Liberty, 1986). Insufficient friction and shear resistance can lead to excessive slip and shearing of the top layers of the surface during braking, limiting the traction available for propulsion. Excessive slip during braking causes the horse to reduce stride length as a means of reducing the longitudinal braking force (Chateau et al., 2010) which adversely affects performance. It may also result in rider falls and accidents (Crevier-Denoix et al., 2010; Murray et al., 2010a). Insufficient friction and shear resistance can lead to shearing of the top layers of the surface and result in increased rotation of the hoof into the surface. Excessive slip will then occur during braking, and traction will be lost for propulsion, which is known to increase fetlock joint extension (Crevier-Denoix et al., 2010). Conversely, during midstance maximal fetlock joint extension is reduced which is likely to reduce the storage and release of passive strain energy in the superficial digital flexor tendon (SDFT) and the suspensory ligament (SL) (Crevier-Denoix et al., 2010). The deficit in passive strain energy is proposed to be compensated by a greater active contribution of the deep digital flexor (DDF) muscles to maintain speed (Crevier-Denoix et al., 2010). Early onset of fatigue in the DDF muscle results in greater passive strain of the SDFT which is then at risk of overloading and injury (Butcher et al., 2007). High quality artificial and natural surfaces are needed for equestrian sports in order to provide an appropriate balance between injury reduction and optimal performance of the equine athlete. Shear resistance of the surface is a complex and important factor in this equation and one that has not been adequately evaluated, in part due to a lack of equipment that has been validated to measure shear resistance of arena surfaces.

Until recently decisions on the design and composition of equine arena surfaces have been based almost entirely on anecdotal observation. This approach has continued in spite of the growing evidence that surfaces can have a major effect on both the performance and the incidence of injury in dressage horses (Murray, Walters, Snart, Dyson, Parkin, 2010b) and eventers (Murray, Singer, Morgan, Proudman, French, 2006) which is similar to the link between surfaces and injuries in racehorses (Oikawa & Kusunose, 2005; Parkin et al., 2004; Peterson, McIlwraith, Reiser, 2008). Thus the development of reliable equipment that can simulate equine movement and loading patterns to quantify the functional characteristics of arena surfaces *in situ* is a vital step towards a process for assessment of equine arena surfaces and developing standard methods to ensure consistency across different competition venues. A drop-hammer system, the Orono biomechanical surface tester (OBST) was developed for measuring racetrack properties (Peterson et al., 2008). The OBST has subsequently been modified for use in the evaluation of equine arena surfaces (Northrop, Martin, Holt, Owen, Hobbs, 2014) and for controlled experiments in the UK by the RACES research team (Holt, Northrop, Owen, Martin, Hobbs, 2014). The apparatus was designed to mimic the loading phase of the gait cycle in a galloping horse. It has two axes of motion that allow measurement of both vertical force and linear shear resistance as the simulated hoof lands and is forced across the surface (Peterson & McIlwraith, 2008). The OBST measures linear shear resistance, but not rotational shear resistance, which may also vary (Nigg & Yeadon, 1987; Setterbo, Yamaguchi, Hubbard, Upadhyaya, Stover, 2011). The drawback to using the OBST to test arena surfaces is that it is designed to replicate the loads and speeds of a horse's forelimb at the gallop (Peterson et al., 2008), or when landing from a jump, but it is not well suited to the lower strain rates associated with slow gaits and rotational movements, such as the dressage canter pirouette.

In human sports an apparatus for measuring rotational traction and friction of turf sports pitches was originally designed in 1975 (Canaway & Bell, 1986). The studded-boot apparatus, known as a torque tester, is now the internationally accepted device used in a number of sports to ensure safety and performance (Twomey, Otago, Ullah, Finch, 2011). In 2010 a traction tester was adapted for use on equine surfaces by replacing the football studs with a studded horse shoe (Blundell, Northrop, Owen, Lumsden, 2010). This device was used for comparison in the present study, however, the apparatus is not considered to be representative of the way a horse lands or turns on a surface, due to the low mass, low vertical drop height and the turning procedure used. Concerns also exist related to the applicability of the test even for human athletes. In particular, significant variation was reported between operators (Blundell et al. 2010), which has been addressed by providing automatic control of the speed of the turning and positioning of the studded disk (McNitt, Middour, Waddington, 1997; Roche, Loch, Poulter, Zeller, 2008). The modified traction tester measures linear and rotational traction simultaneously (Brosnan, McNitt, Serensits, 2009). However, neither design has been adapted for the speed and loads associated with the equine athlete.

Other methods for assessing the horizontal properties of equine surfaces have included cadaver limbs attached to a drag apparatus instrumented with load cells (Clanton, Kobluk, Robinson, Gordon, 1991) and more recently a track testing device that measured linear shear resistance and a shear vane tester that measured shear stress and surface cohesion (Setterbo et al., 2012). The latter of these designs (Setterbo et al., 2012) has been used to make measurements on dirt and synthetic racetracks, but both designs were reported to have limitations in relation to replicating equine locomotion. Shear resistance on turf racetracks is normally measured using a GoingStick (Caple, James, Bartlett, 2012), where a flat blade is pushed into the surface and then rotated about its base to an angle of 45° to measure the force needed to push and turn the blade (Peterson et al., 2012). A linear relationship between shear resistance using a GoingStick and peak torque resistance using a studded disk apparatus was found on turf sport pitches (Caple et al., 2012). This relationship has only been investigated on turf surfaces which have a relatively homogeneous cross section that is necessary for the health of the turf. This is usually not the case with racing surfaces (Mahaffey, Peterson, McIlwraith, 2012) or with arena surfaces composed of fibre and sand (with or without the addition of wax). In these surfaces a hard pan layer is set up under the shallow top surface that supports the hoof during propulsion or landing. The non-homogeneity of these surfaces makes them unsuitable for evaluation using a penetrometer type device such as the GoingStick for measuring shear resistance.

An appropriate mechanical apparatus for measuring the rotational shear properties of equine sport surfaces is not available. Current methods used in human biomechanics do not adequately represent the hoof-surface interaction and current equine specific measurements do not measure rotational shear. For this reason a new piece of equipment, named the Glen Withy torque tester (GWTT), was designed that was capable of measuring rotational torque whilst under a consistently applied quasi-static vertical load. The device is named after its designer which provides the potential for it to become a piece of standardised equipment in the future. This study compares data from the GWTT with data from other equipment used to test arena surfaces (OBST and traction tester) to assess its ability to provide distinct information describing the equine arena surface response. In addition, by using different pieces of equipment, that apply different loading rates, the effect of strain rate dependency on shear resistance can be explored. The aims of the study were to use the GWTT for measuring equine arena surfaces and to compare its results with those from the OBST and traction tester within and between surfaces. Linear and rotational shear resistance may vary for the same surface (Nigg & Yeadon, 1987), and arena surfaces are reported to be strain rate dependant. It was therefore hypothesised that any relationship between measurements from the OBST compared to the GWTT and traction tester for the same surface, in particular measures of rotational and longitudinal shear, would be non-linear and complex and would not be expected to be well correlated. Also, even if a correlation between these devices was observed on a particular surface it would not necessarily be applicable to other surfaces. Therefore, the initial investigations using the GWTT and the other devices were performed using two different types of surfaces.

2 Methods

The construction and measurements made by the traction tester and a first-generation OBST have been previously described (Blundell et al., 2010; Peterson et al., 2008). In this work, we give construction details of the GWTT, and describe the types of measurement that are made by the traction tester, GWTT, and arena-surface modified OBST. The three devices are shown in Fig. 1.

2.1 Equipment

2.1.1 Glen Withy Torque Tester (GWTT)

The GWTT is an instrumented hoof design built into a support structure that can carry up to 100 kg mass and that has suitable attachments for a tractor or similar sized equipment to move it easily. The support structure of the GWTT was based on a vertical central column and horizontal cross member of 75 mm box section (see Figure 1). The central column houses a 25 mm diameter main shaft that rotates on ball bearing races (47 mm outer diameter (o.d.)) at the top and bottom of the shaft. In addition, 2 ball bearing thrust races (50 mm o.d. at the top and 100 mm o.d. at the bottom) carry the vertical thrust force. Attached to the bottom of the main shaft is a housing that sandwiches a piezoelectric dynamometer (Kistler Instruments Ltd. Hook, Hampshire, UK, model 9271A; model 9272 is the currently available equivalent), through which applied vertical force and dynamic torque are applied and measured respectively. A horseshoe is fixed to the bottom of the housing at the base. At the top of the main shaft is a square fitting drive to which a two-ended handle can be secured when in use to provide complementary torque. The amount of rotational twist is measured by a dial indicator fitted to the square section. The housing of the central column supports adjustable bars on both sides to allow easy attachment and removal of circular masses. A control box to house the instrumentation is also secured to the central column. The horizontal cross member is designed to be attached to the bottom two links of a type 1 three-point tractor implement linkage. Attached to the cross member is a spring loaded linear potentiometer (Novotechnik, Ostfildern, Germany, model TRS 100) with a foot at its base and this measures the vertical displacement of the horseshoe into the surface as torque is applied. An attachment on the column for the top tractor link of the three-point linkage is also provided (see supplementary materials for assembly drawings). Once the GWTT is secured in the three-point-linkage vertical stability can be maintained, but with sufficient slack to prevent resistance at the links during testing which might otherwise influence the torque measurements. To obtain dynamic measurements the equipment is lowered slowly to the ground on the three point linkage, once slack against the links the handle is turned through a measured angle by the same operator and then raised immediately after turning is complete. Typical hoof rotations during locomotion are shown in Fig. 2, which highlights the point in the stance phase most relevant to the operation of the equipment.

Three different masses were examined as part of the GWTT validation process. The mass of the apparatus was 16 kg, which was used as a baseline measurement. Addition of a 30 kg mass (total 46 kg) was selected as being equivalent to the mass used by the traction tester (Blundell et al., 2010). Addition of a 100 kg mass (total 116 kg) was used which provided approximately half the mass of a pony and one fifth the mass of a horse. Three turning angles (40^o, 90^o, 140^o) were selected to give an indication of the effect of turning by different degrees on the variability of the data produced by the apparatus. The minimum angle of 40^o was chosen to represent the rotation of the horse’s body about a grounded limb, for example during a canter pirouette where the leading hind limb is in contact with the ground for almost 80% of the stride (Burns & Clayton, 1997). As maximum torque is normally produced prior to shear failure, turning the GWTT through the maximum possible angle ensured that the separate events of shear failure and maximum torque were most likely to be captured. While the central column was able to be turned through an angle more than 140°, a maximum angle of 140 ° was used. A rotation of the device of 90° provided an intermediate value. Turning speed was estimated and reproduced through practice and repetition of the same operator.

The voltage signals from the dynamometer were amplified (Kistler Instruments Ltd. Hook, Hampshire, UK, charge amplifier model 5073) and these, together with the linear potentiometer signals were then converted to a digital signal (National Instruments UK, Newbury, Berkshire, UK, A/D converter model NI USB-6210). All were sampled simultaneously for 10 s at 100 Hz in Labview (National Instruments UK, Newbury, Berkshire, UK). Peak torque (T_{max}), peak vertical displacement (D_{max}) and mean vertical force (GRF_{mean}) were extracted from the digital data acquired using the device.

2.1.2 Traction Tester

The traction tester is a simple design that uses a steel rod attached to a circular, screw-on base with a studded horseshoe on the underside of the base (Fig. 1). Three circular, 10 kg masses each with a central hole are secured to the rod above the base. Two handles at the top of the apparatus allow it to be lifted and dropped. The operator lifted the device to a height of 0.2 m before releasing it, to allow the horseshoe to embed into the surface. Once the apparatus had been dropped, a torque wrench was applied to the top of the rod and then was rotated until shear failure of the surface occurred. The maximum value recorded (T_{maxTT}) on the torque wrench prior to failure was tabulated for each trial. The same experienced researcher was used throughout to reduce variability, consistent with general practice (Blundell et. al, 2010).

2.1.3 Orono Biomechanical Surface Tester (OBST)

The operation of this apparatus has been described previously (Peterson et al., 2008). For these tests the hoof was dropped through a distance of 0.86 m down the rails which were at an angle of 8° from the vertical. Temporal data from a tri-axial load cell (Kistler Instruments Ltd. Hook, Hampshire, UK, type 9347C) and string potentiometer (Celesco, Chatsworth, CA, USA, model PT5A) were recorded simultaneously (National Instruments UK, Newbury, Berkshire, UK, A/D converter model NI USB-6210) for 2 s in Labview at 2000 Hz (National Instruments UK, Newbury, Berkshire, UK). The files were converted to a suitable ASCII format and then imported into Visual 3D. Landing force was determined from the vertical component of force from the tri-axial load cell using a threshold of 50 N and peak vertical force from the maximum value recorded ($GRFV_{max}$). Landing speed was derived from the string potentiometer displacement data and the longitudinal component obtained using trigonometry. Slip distance was then measured by double integration of the longitudinal component of force, where the force was divided by mass prior to the first integration and landing speed was used as a constant for the second integration. Slip distance during loading (Slip) was then measured from landing to peak vertical force. The longitudinal force component was rectified and the maximum value identified to obtain peak longitudinal force ($GRFH_{max}$).

2.2 Initial validation of GWTT measurements

2.2.1 Procedure

A calibration measurement of the coefficient of friction of the GWTT shoe on black mild steel plate was carried out in the laboratory using a calibrated 8 camera Qualisys Oqus system capturing data at 100 Hz. Markers were attached at the top and bottom edge of a 1 m flat black steel plate and four markers were attached to the underside of a shoe made for the GWTT. Trials were captured as the shoe slid down the angled steel plate with the angle of the plate being varied in small increments from trial to trial to provide data that included speeding up, constant velocity and slowing down. Ten tests were recorded with the open end facing up the slope and a further 10 tests with the open end facing down the slope. The angle was varied for each trial. In addition, four repeated measurements of the angle required to initiate movement of the shoe were recorded in four different orientations of the horse shoe; front, back, left, right.

Measurement of the coefficient of friction of the GWTT shoe on black mild steel was carried out in-situ using the GWTT and a flat black mild steel plate with steel grips welded to the underside. This plate was firmly secured into an arena surface prior to testing. The GWTT was loaded with 100 kg mass, lowered onto the steel plate and rotated slowly through 90° and the load removed following turning. Eight repeated measurements were recorded.

2.2.2 Data Analysis

For the laboratory based measurements, markers on the flat plate and the shoe were tracked and exported to Visual 3D. The angle of the plate was determined from the marker coordinates and the shoe velocity during sliding was derived. Average acceleration was calculated over the last third of the slope. The coefficient of friction was determined by calculating the tangent of the angle. Static friction mean and standard deviation (s.d.) were tabulated. Linear regression was used to determine the coefficient of friction value at zero acceleration for sliding friction.

For *in-situ* measurements T_{max} and GRF_{mean} were extracted from the GWTT and the frictional force calculated from the shoe dimensions. The coefficient of friction was calculated by dividing the frictional force by GRF_{mean}. Mean and s.d. were calculated and results from the *in-situ* test were compared to the laboratory sliding friction results.

2.3 In-situ testing of GWTT, OBST and traction tester

2.3.1 Procedure

Two artificial surfaces were used; a waxed sand and fibre surface and a non-waxed sand and fibre surface. Each surface was tested using 5 repeats at 9 locations with each piece of equipment separately (see Fig. 3). The order of testing of additional mass (0, 30 and 100 kg) and turn angle (40^o, 90^o and 140^o) was randomised.

A surface sample was also taken from each location. The top layer of surface was removed and a minimum of 100 g of sub-surface was placed into a labelled plastic bag and sealed. To evaluate moisture content 100 g of the surface from each sample was weighed out and placed in a pre-weighed heat-proof tray that was baked in an oven at 38 ^{o}C for 48 h. The samples were then re-weighed and the moisture content determined using ISO/TS 17892-1:2004.

Three temperature loggers (Gemini Data Loggers, Chichester, West Sussex, UK, model Tinytag Talk 2) were utilised in the week prior to data collection. One was placed 100 mm below the surface of the test track, one was placed on top of the surface, and the third was placed above the surface to measure the air temperature. The loggers were programmed to record temperature every 10 min. The mean temperature ± standard error in each position was calculated for the week leading up to data acquisition. The measurements of moisture for the unwaxed surface and temperature for the waxed surface are consistent with data reported in the relevant literature (Bridge, Peterson, McIlwaith, Beaumont, 2010; Ratzlaff et al., 1997). However, for consistency both temperature and moisture were measured for both surfaces.

2.3.2 Data Analysis

Statistical analyses were performed in SPSS (IBM Corp., Armonk, NY, USA) with significance set at $P<.05$. Data were screened for normality using a Kolmogorov-Smirnov test. To identify the most appropriate protocol for use of the GWTT in relation to applied load and turn angle, a 3 (mass) x 3 (turn angle) MANOVA was used with T_{max} and $D_{\max}$ as dependant variables with Bonferroni post hoc tests on significant variables. To investigate consistency of loading the limits of agreement between applied load and GRF_{mean} when separated by mass and turn angle were determined (Bland & Altman, 1999). To evaluate the relationship between measurements 1) on the same surfaces and 2) between surfaces made by each piece of equipment, a partial correlation controlling for significant factors identified in the MANOVA was used and 1) controlling for surface and 2) without controlling for surface. Finally, a MANOVA was used for all measurements to compare the difference between the two surfaces, with mass as a covariate. Stratified bootstrapping (1000 samples) was used on all non-normally distributed measurements when conducting parametric tests.

3 Results

A typical raw data file is shown in Fig. 4 from the GWTT. Data were normally distributed for D_{max}, T_{max} and *Slip.* All other data were not normally distributed. The coefficient of sliding friction determined from the lab-based testing was 0.196±0.006 (mean±C.I.) (see Fig. 5) and for *in-situ* testing was 0.173±0.021 (mean±s.d.) for the shoe on black steel plate. The coefficient of static friction was 0.238±0.018 (mean±s.d.).

The moisture contents for the waxed surface and non-waxed surface were 5.1±2.11 % and 17.8±1.68 % respectively (mean ± s.d.). Air temperature, surface temperature and sub-surface temperature in the week leading up to data collection measured in and above the waxed surface were 19.5±0.1 ^{o}C, 22.5±0.2 ^{o}C, and 20.2±0.1 ^{o}C respectively. Weather conditions were considered to be temperate on the day of testing and there was no rainfall.

Mean ± s.d. results for T_{max} and D_{max} with respect to mass and turn angle for the GWTT, for both surfaces combined, are shown in Table 1. A significant main effect (P<.001) of mass was found in the model with significant differences for both T_{max} F(2)=582.227, $P<.001$ and D_{max} F(2)=6.754, $P = .002$. No significant differences were found for turn angle and there was no significant interaction between mass and turn angle.

The limits of agreement between GRF_{mean} and the applied load separated by mass are shown in Fig. 6 together with the percentage of measurements that fell outside of ±1 s.d. limits for each turn angle. The mean difference between measurements was -94.3±46.2, -75.0±106.3 and -23.1±75.5 N for 0, 30 and 100 kg masses respectively. A turn angle of 40° was most often outside of the limits of agreement followed by 140°.

The relationship between measurements is shown in Table 2. When controlling for mass, a weak negative relationship was found between D_{max} from the GWTT and T_{maxTT} from the traction tester (R =-.257, P =.019). A weak positive relationship was found between D_{max} and *Slip* (R =.234, P=.033). No other relationships between variables were found.

Measurements for all equipment (mean ± s.d.) are shown in Figure 7 separated by surface and for the GWTT also separated by mass. A significant main effect (P<.001) was found for surface with significant differences in T_{max} F(1)=12.38, P =.001, D_{max} F(1)=10.57, P=.002, and $GRFV_{max}$ F(1)=15.37, P<.001. No other measurements were found to differ significantly between surfaces.

4 Discussion

This study examined the capability of a newly developed piece of equipment, known as the Glen Withy Torque Tester (GWTT), to measure rotational torque on equestrian arena surfaces. The most appropriate protocols were compared over a range of applied loads and turn angles and measurements made with the GWTT were compared to measurements from existing equipment used to evaluate arena surfaces. It was hypothesised that any relationship between measurements, in particular that between $GRFH_{max}$, slip and T_{max}, would be non-linear and complex. When pooling the data a weak, but significant linear relationship was found between the GWTT and OBST, which measure rotational compared to linear shear resistance and where markedly different loads and loading rates are applied to the surface. This relationship weakened when controlling for surface. These findings suggest that the hypothesis might, in part, be cautiously rejected when comparing linear slip to vertical displacement of the GWTT into the surface, providing a sufficient number of data points are compared to account for location specific variability. The lack of correlation between other measurements from the GWTT compared to the OBST supported the hypothesis.

4.1 Identification of the most appropriate protocol for the GWTT

The mass applied to the GWTT had a significant effect on the T_{max} and D_{max} readings where a greater mass was associated with higher values. Higher traction values have been measured previously with devices suitable for testing sports surfaces when a greater vertical load was applied due to the greater resistance to movement (Baker, 1991; Brosnan et al., 2009; Goodall, Guillard, Dest, Demars, 2005; McNitt et al., 1997). When evaluating each measured mass for reliability against the applied load, it was found that the minimum amount of bias in measured mass occurred when 100 kg mass was attached to the GWTT. This may be due to the attachment of the GWTT to a 3 point linkage where the heavier mass was more stable once on the ground and as such it may have been easier to apply a rotational torque without inadvertently altering the vertical force. The difference may also have been influenced by spatial inconsistencies, which occur during the slide of the hoof on the surface during the initial contact of the hoof on the arena. The resulting hoof prints and movement of material are difficult to remove with maintenance, but the effect of the prints is reduced at higher loads since the deeper levels of the surface which are measured at higher loads are not impacted as much as the top surface of the arena.

Turning angle did not have a significant effect on T_{max} or D_{max} recorded with the GWTT, but a 90^{o} turn angle provided the most consistent vertically applied load compared to the other two angles for all masses. For at 40^{o} angle the mass may not have been as consistently applied, due to the shorter time needed to make the turn before the GWTT was lifted again. At 140^{o} angle, the operator reported that it was difficult to achieve a consistent purchase on the handle. A lack of control whilst rotating a traction device was responsible for low reliability in measurements during a study by Twomey et al. (2011). This, in conjunction with the angle not representing a particular activity carried out by horses, meant that using a turning angle of 40^{o} or 90^{o} was more appropriate. One complete canter pirouette is usually completed in 6-8 strides, which suggests that the body will turn through 45-60^{o} over an inside hind limb that is grounded for the majority of the turn if the movement is executed correctly (Burns & Clayton, 1997). Similarly, a show jumping horse is expected to turn as tightly as possible during the jump off round of a class (the jump off is a shorter version of the original course and is to be completed as fast as possible). Crevier-Denoix et al. (2014) recently reported that a pure static rotation of the hoof in the surface rarely occurs, as the hoof also slides transversally and longitudinally throughout turning, which is not replicated by the GWTT. In addition, GWTT does not simulate the loading conditions during propulsion. The

GWTT is rigid, simulating a turn of a planted foot under a quasi-static load, so further work is required to investigate it's applicability to the biomechanics of turning. The results can be considered as promising though with respect to the magnitude of peak torque (T_{max}), since they were comparable with those found by Chateau et al. (2013) in horses trotting in circles on different surfaces.

The accuracy of the measurements from the GWTT were compared to standard laboratory tests for static and sliding friction of the shoe on black mild steel. The coefficient of static friction for steel on steel with an oxide coating was reported to be 0.27 and for sliding friction with a greasy surface 0.09 - 0.19 (Engineers Handbook, 2006). These values are comparable with the laboratory based test results and *in-situ* test results obtained in this study, suggesting that the GWTT provides sufficient accuracy of measurement for friction and shear resistance when loaded with a 100 kg mass.

Turning speed was subjectively controlled in the current study. As the surfaces tested are strain rate dependant (Reiser et al., 2000), small differences in turning speed may have influenced measurements from the GWTT. The GWTT has since been instrumented with an angular potentiometer (see supplementary information), which will allow turning speed to be taken into account in future work. This will also allow for a more detailed examination of maximum torque and shear failure events using higher sampling frequencies.

4.2 Relationships between measurements

The relationship between the vertical displacement of the GWTT (D_{max}) and slip measured from the OBST suggests that more slip would be expected on a surface where the top layer deforms more under an applied load. Greater deformation is usually associated with more particle movement as a consequence of large pore spaces and less angularity in sand shape (Bridge, Mahaffey, Peterson, 2014). Moisture content, polymer binder and fibre content are also relevant. The relationship was thought to be weak due to the viscoelastic nature of the surfaces, particularly as the moisture content varied between surfaces and across locations. The surface specific increase in T_{max} with an increase in D_{max} suggests that rotational torque increases as the shoe is displaced further into the surface vertically, possibly due to increasing forces from the surrounding substrate (Burn, 2006). This contradicts the relationship found between D_{max} recorded with the GWTT and T_{maxTT} measured using the traction tester, which suggests that surfaces with greater vertical deformation offer less traction. An explanation may relate to the difference in function between the devices. The traction tester tended to be pulled out from the surface, whereas the GWTT tended to “screw down” into the surface. The traction measurement may therefore be indicative of the looseness of the cushion, rather than the shear strength of the surface as a whole. The disputed reliability of the traction tester may also have influenced these results (Twomey et al., 2011). The surface specific relationships found for the OBST show the intrinsic link between the components of force from a dynamic impact and data derived from forces, in this case slip.

The lack of a relationship between other measurements highlights the complexity of arena surface functional properties and their measurement. The need for truly functional measurements of arena surfaces is therefore clearly supported by these results. These surfaces usually have a loose upper layer which allows motion of the hoof early in the loading phase supported by an underlying firm layer. This stratification accentuates the non-linear character of the materials since the initial stiffness of the surface is very low but it increases with an increase in the load. This increase in stiffness as a function of loading occurs in both vertical and horizontal directions. At the same time the strain rate sensitivity of the loading in shear is characteristic of a porous material where flow of water or wax is highly dependent on the loading rate (Bridge, Peterson, McIlwaith, 2011). This supports the principle that the loading of the surface must represent the rate and load of the hoof for the particular usage of the surface.

4.3 Comparison of surface behaviour

Differences between the waxed and non-waxed surfaces were detected by the GWTT and the OBST, but not the traction tester. However, only the GWTT was able to detect significant differences between the surfaces in relation to shear resistance characteristics.

The significantly higher torsional resistance measurements and the significantly lower displacement measurements for the waxed surface when compared with those for the non-waxed surface (all obtained using the GWTT), indicates that the waxed surface exhibits greater shear resistance than the non-waxed surface. Although not significant, the reduction in slip for the waxed surface also suggests that this surface has more grip. In baseball playing surfaces with higher soil bulk density levels are associated with significantly increased linear and rotational traction (Brosnan et al., 2009), which is thought to be due to a higher soil bulk density causing greater resistance to the movement of the athlete’s studs through the profile

(Brosnan et al., 2009). Less surface deformation together with reduced horizontal slip distance was also found by Crevier-Denoix et al. (2013) when comparing horses cantering on turf versus an all-weather waxed surface, but in this case the waxed surface had greater deformation and slip. Chateau et al. (2009) also described an increased duration of the braking phase on all-weather waxed sand compared to crushed sand. The wax component of a surface may therefore be less of a determinant of shear resistance and grip than, for instance the surface density. Surface density did not, however, affect the traction values recorded on synthetic equine surfaces using the traction tester (Holt et al. 2014), although these findings may simply indicate that the equipment is not appropriate for such measurements rather than indicating the lack of a relationship between traction and bulk density.

The similarity of $GRFH_{max}$ between surfaces was also somewhat surprising, as greater maximum horizontal force has been measured on crushed sand in comparison to an all-weather waxed track in trotters wearing a dynamometric horseshoe (Robin et al., 2009). In addition, similarity in $GRFH_{max}$ infers similarity in shear resistance and slip, which was not found. One of the confounding factors in the study of slip and shear resistance was the damping ability of the surface. Crevier-Denoix et al. (2013) reported that waxed surfaces are more effective in damping lower frequency concussion events. As such, indirect measurements of slip may be difficult to interpret alone. Using the horizontal force measurements to determine slip appears to be more sensitive to changes in surface type for the OBST, rather than considering horizontal forces alone.

When comparing the range of measurements taken from each surface it was also apparent that greater variability was consistently found on the non-waxed surface. Wax is reported to improve surface consistency by reducing the effects of moisture (Bridge, Peterson, McIlwaith, 2012), which was relatively high in the non-waxed surface on the test date. In addition, the fibre type and distribution through the surface may have influenced variability, as longer fibres were evident in the non-waxed surface.

Using the GWTT it was also possible to calculate the coefficient of sliding friction, which was found to be 0.40 ±0.06 on the waxed surface and 0.37 ±0.11on a non-waxed surface. These values are lower than the values of 0.585 to 0.741 reported when dragging cadaver hooves across a dirt track (Clanton et al., 1991), and lower than for human sporting activities (Shorten, Hudson, Himmelsbach, 2003). In the study by Clanton et al. (1991) the build up of material in front of the hooves may have artificially increased the shear resistance. The requirement for slide in equine activities is expected to be greater than in human activities. Concrete, asphalt and rubber surfaces (smooth and patterned) have been shown to have a static coefficient greater than 0.7, which limits the potential for hoof slip (McClinchey et al. 2004). Gustås et al. (2006) suggested that a high amount of friction during the hoof-surface interaction increases vibration transients, resulting in mechanical stress to the structures of the distal limb and possible injury, thus implying that a surface with a lower coefficient of friction would be more favourable. Harder equine surfaces are commonly reported to have increased grip, which does not support the $GRFV_{max}$ results compared to the results from the GWTT. However, the $GRFV_{max}$ values are most likely to have been lower on the waxed surface because the inclusion of a permavoid system in the sub-base has previously been shown to significantly reduce peak vertical force using the OBST (Holt et al., 2014). This highlights the need to use the OBST for measurement of the complete surface *in-situ*, as many of the current measurement equipments are not capable of detecting differences below the surface that the horse will experience.

5 Conclusion

In this study the GWTT was shown to be the only equipment tested capable of identifying and measuring the difference in shear resistance of a waxed surface compared with a non-waxed surface. This is an important consideration in equestrian sports for facilitating optimal performance without compromising safety. Since the characteristics and performance of arena surfaces are complex, it may be necessary to use more than one piece of equipment to adequately characterise all the important functional properties. Based on the results presented here data from the torque tester did not add significantly to the information provided by the OBST and the GWTT. Future studies should carry out a more extensive evaluation of the functional properties measured by the OBST and the GWTT to explore the complex relationship between linear and rotational shear resistance under different loading conditions.

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Figure Captions

Fig. 1: Photograph of: a) the Glen Withy torque tester (GWTT), b) the Orono biomechanical surface tester (OBST) and c) the traction tester.

Fig.2: Typical rotational (R) and longitudinal (L) motions of the hoof during the hoof-surface interaction viewed laterally a) footstrike, b) secondary impact, c) breakover where pitch rotation and longitudinal sliding occurs. Frontal and solar views of d) roll rotation, and e) yaw rotation which is most likely to occur during turning and are usually accompanied by longitudinal and/or medio-lateral sliding. The GWTT replicates motion and torque as shown in e).

Fig. 3: Plan of the data collection area used to test each of the two surfaces. Each mass and each turn angle were tested at one of the locations. The order was randomised. The testing areas were marked using flags and were 3 m × 4 m in size.

Fig. 4: A typical graph from the GWTT. The graph illustrates signals for GRF_{mean} (the average of vertical GRF values over the time illustrated (kN)), D_{max} x 10 (mm), T_{max} (Nm).

Fig. 5: Results of laboratory sliding friction tests showing the coefficient of friction value for the shoe on black mild steel intersection of the x-axis at 0.196±0.06 (mean±C.I.).

Fig. 6: Bland and Altman (1999) plot of the limits of agreement between GRF_{mean} from the GWTT and the load applied ((machine mass + applied mass) x gravity) (N), a) 16 + 0 kg applied load, b) 16 + 30 applied load, c) 16 + 100 kg applied load. The dotted horizontal lines show the limits of agreement at 1 standard deviation from the mean. Data points outside of the dotted lines may be considered as inconsistencies in vertical loading of the GWTT.

Fig. 7: Measured differences between surfaces for the GWTT: T_{max} (Nm), D_{max} x 10 (mm); the OBST: *Slip* (mm), $GRFH_{max}$ (kN), $GRFV_{max}$ (kN); and the traction tester: T_{maxTT} (Nm). Error bars represent the standard deviation. * Significant differences ($P<.05$) were found for T_{max} and D_{max} and $GRFV_{max}$.