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Title	Comparison of equipment used to measure shear properties in equine arena surfaces
Type	Article
URL	https://clok.uclan.ac.uk/12452/
DOI	https://doi.org/10.1016/j.biosystemseng.2015.07.006
Date	2015
Citation	Lewis, Kate, Northrop, Alison J, Crook, Glen Martin, Mather, John, Martin, Jaime H, Holt, Danielle, Clayton, Hilary M, Roepstorff, Lars, Peterson, Michael et al (2015) Comparison of equipment used to measure shear properties in equine arena surfaces. Biosystems Engineering, 137. pp. 43-54. ISSN 1537-5110
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It is advisable to refer to the publisher's version if you intend to cite from the work.
https://doi.org/10.1016/j.biosystemseng.2015.07.006

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1   **Abstract**

2   The design of a novel apparatus, the Glen Withy torque tester (GWTT), for measuring

3   horizontal shear properties in equine sport surfaces is described. Previous research has

4   considered the effect of vertical loading on equine performance and injury but only limited

5   discussion has concerned the grip or horizontal motion of the hoof. The horizontal support of

6   the hoof by the surface must be sufficient to avoid excess slip without overloading the limb.

7   The GWTT measures the torque necessary to twist an artificial hoof that is being pushed into

8   the surface under a consistently applied vertical load. Its output was validated using a steel

9   surface, then was used to test two sand and fibre surfaces (waxed and non-waxed) through

10   rotations of 40-140°, and vertical loads of 156-980 N. An Orono biomechanical surface

11   tester (OBST) measured longitudinal shear and vertical force, whilst a traction tester

12   measured rotational shear after being dropped onto the surfaces. A weak, but significant,

13   linear relationship was found between rotational shear measured using the GWTT and

14   longitudinal shear quantified using the OBST. However, only the GWTT was able to detect

15   significant differences in shear resistance between the surfaces. Future work should continue

16   to investigate the strain rate and non-linear load response of surfaces used in equestrian

17   sports. Measurements should be closely tied to horse biomechanics and should include

18   information on the maintenance condition and surface composition. Both the GWTT and the

19   OBST are necessary to adequately characterise all the important functional properties of

20   equine sport surfaces.

21

22   **Key Words**

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

24   **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	

1

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)

25

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

3

59   prevents slipping, tripping or falling (Murray, Walters, Snart, Dyson, Parkin, 2010a) and

60   provides traction for propulsive effort (Crevier-Denoix et al., 2010). Excessive resistance to

61   the horizontal motion or rotation is expected to result in an earlier onset of hoof braking and

62   an increase in the magnitude of the peak stress and loading rate in the limb (Gustås, Johnston,

63   Drevemo, 2006). Reduced horizontal motion of the hoof has been associated with surface

64   hardness (Wilson & Pardoe, 2001; Orlande, Hobbs, Martin, Owen, Northrop, 2010) and

65   harder surfaces tend to increase the magnitude of higher frequency vibrations during impact

66   and limb loading (Chateau et al., 2009). The high frequency components of the loading are

67   reported to be attenuated mainly by the hoof, and the magnitude of peak stress is gradually

68   damped proximally by the distal limb structures (Lanovaz, Clayton, Watson, 1998;

69   Willemen, Jacobs, Schamhardt, 1999). High frequency loading damages bone and articular

70   cartilage predisposing to the development of osteoarthritis (Folman, Wosk, Voloshin, Liberty,

71   1986). Insufficient friction and shear resistance can lead to excessive slip and shearing of the

72   top layers of the surface during braking, limiting the traction available for propulsion.

73   Excessive slip during braking causes the horse to reduce stride length as a means of reducing

74   the longitudinal braking force (Chateau et al., 2010) which adversely affects performance. It

75   may also result in rider falls and accidents (Crevier-Denoix et al., 2010; Murray et al.,

76   2010a). Insufficient friction and shear resistance can lead to shearing of the top layers of the

77   surface and result in increased rotation of the hoof into the surface. Excessive slip will then

78   occur during braking, and traction will be lost for propulsion, which is known to increase

79   fetlock joint extension (Crevier-Denoix et al., 2010). Conversely, during midstance maximal

80   fetlock joint extension is reduced which is likely to reduce the storage and release of passive

81   strain energy in the superficial digital flexor tendon (SDFT) and the suspensory ligament

82   (SL) (Crevier-Denoix et al., 2010). The deficit in passive strain energy is proposed to be

83   compensated by a greater active contribution of the deep digital flexor (DDF) muscles to

84   maintain speed (Crevier-Denoix et al., 2010). Early onset of fatigue in the DDF muscle

85   results in greater passive strain of the SDFT which is then at risk of overloading and injury

86   (Butcher et al., 2007). High quality artificial and natural surfaces are needed for equestrian

87   sports in order to provide an appropriate balance between injury reduction and optimal

88   performance of the equine athlete. Shear resistance of the surface is a complex and important

89   factor in this equation and one that has not been adequately evaluated, in part due to a lack of

90   equipment that has been validated to measure shear resistance of arena surfaces.

91

4

92   Until recently decisions on the design and composition of equine arena surfaces have been

93   based almost entirely on anecdotal observation. This approach has continued in spite of the

94   growing evidence that surfaces can have a major effect on both the performance and the

95   incidence of injury in dressage horses (Murray, Walters, Snart, Dyson, Parkin, 2010b) and

96   eventers (Murray, Singer, Morgan, Proudman, French, 2006) which is similar to the link

97   between surfaces and injuries in racehorses (Oikawa & Kusunose, 2005; Parkin et al., 2004;

98   Peterson, McIlwraith, Reiser, 2008). Thus the development of reliable equipment that can

99   simulate equine movement and loading patterns to quantify the functional characteristics of

100   arena surfaces *in situ* is a vital step towards a process for assessment of equine arena surfaces

101   and developing standard methods to ensure consistency across different competition venues.

102   A drop-hammer system, the Orono biomechanical surface tester (OBST) was developed for

103   measuring racetrack properties (Peterson et al., 2008). The OBST has subsequently been

104   modified for use in the evaluation of equine arena surfaces (Northrop, Martin, Holt, Owen,

105   Hobbs, 2014) and for controlled experiments in the UK by the RACES research team (Holt,

106   Northrop, Owen, Martin, Hobbs, 2014). The apparatus was designed to mimic the loading

107   phase of the gait cycle in a galloping horse. It has two axes of motion that allow measurement

108   of both vertical force and linear shear resistance as the simulated hoof lands and is forced

109   across the surface (Peterson & McIlwraith, 2008). The OBST measures linear shear

110   resistance, but not rotational shear resistance, which may also vary (Nigg & Yeadon, 1987;

111   Setterbo, Yamaguchi, Hubbard, Upadhyaya, Stover, 2011). The drawback to using the OBST

112   to test arena surfaces is that it is designed to replicate the loads and speeds of a horse's

113   forelimb at the gallop (Peterson et al., 2008), or when landing from a jump, but it is not well

114   suited to the lower strain rates associated with slow gaits and rotational movements, such as

115   the dressage canter pirouette.

116

117   In human sports an apparatus for measuring rotational traction and friction of turf sports

118   pitches was originally designed in 1975 (Canaway & Bell, 1986). The studded-boot

119   apparatus, known as a torque tester, is now the internationally accepted device used in a

120   number of sports to ensure safety and performance (Twomey, Otago, Ullah, Finch, 2011). In

121   2010 a traction tester was adapted for use on equine surfaces by replacing the football studs

122   with a studded horse shoe (Blundell, Northrop, Owen, Lumsden, 2010). This device was

123   used for comparison in the present study, however, the apparatus is not considered to be

124   representative of the way a horse lands or turns on a surface, due to the low mass, low

125   vertical drop height and the turning procedure used. Concerns also exist related to the

126   applicability of the test even for human athletes. In particular, significant variation was

127   reported between operators (Blundell et al. 2010), which has been addressed by providing

128   automatic control of the speed of the turning and positioning of the studded disk (McNitt,

129   Middour, Waddington, 1997; Roche, Loch, Poulter, Zeller, 2008). The modified traction

130   tester measures linear and rotational traction simultaneously (Brosnan, McNitt, Serensits,

131   2009). However, neither design has been adapted for the speed and loads associated with the

132   equine athlete.

133

134   Other methods for assessing the horizontal properties of equine surfaces have included

135   cadaver limbs attached to a drag apparatus instrumented with load cells (Clanton, Kobluk,

136   Robinson, Gordon, 1991) and more recently a track testing device that measured linear shear

137   resistance and a shear vane tester that measured shear stress and surface cohesion (Setterbo et

138   al., 2012). The latter of these designs (Setterbo et al., 2012) has been used to make

139   measurements on dirt and synthetic racetracks, but both designs were reported to have

140   limitations in relation to replicating equine locomotion. Shear resistance on turf racetracks is

141   normally measured using a GoingStick (Caple, James, Bartlett, 2012), where a flat blade is

142   pushed into the surface and then rotated about its base to an angle of 45° to measure the force

143   needed to push and turn the blade (Peterson et al., 2012). A linear relationship between shear

144   resistance using a GoingStick and peak torque resistance using a studded disk apparatus was

145   found on turf sport pitches (Caple et al., 2012). This relationship has only been investigated

146   on turf surfaces which have a relatively homogeneous cross section that is necessary for the

147   health of the turf. This is usually not the case with racing surfaces (Mahaffey, Peterson,

148   McIlwraith, 2012) or with arena surfaces composed of fibre and sand (with or without the

149   addition of wax). In these surfaces a hard pan layer is set up under the shallow top surface

150   that supports the hoof during propulsion or landing. The non-homogeneity of these surfaces

151   makes them unsuitable for evaluation using a penetrometer type device such as the

152   GoingStick for measuring shear resistance.

153

154   An appropriate mechanical apparatus for measuring the rotational shear properties of equine

155   sport surfaces is not available. Current methods used in human biomechanics do not

156   adequately represent the hoof-surface interaction and current equine specific measurements

157   do not measure rotational shear. For this reason a new piece of equipment, named the Glen

158   Withy torque tester (GWTT), was designed that was capable of measuring rotational torque

159   whilst under a consistently applied quasi-static vertical load. The device is named after its

160   designer which provides the potential for it to become a piece of standardised equipment in

161   the future. This study compares data from the GWTT with data from other equipment used

162   to test arena surfaces (OBST and traction tester) to assess its ability to provide distinct

163   information describing the equine arena surface response. In addition, by using different

164   pieces of equipment, that apply different loading rates, the effect of strain rate dependency on

165   shear resistance can be explored. The aims of the study were to use the GWTT for measuring

166   equine arena surfaces and to compare its results with those from the OBST and traction tester

167   within and between surfaces. Linear and rotational shear resistance may vary for the same

168   surface (Nigg & Yeadon, 1987), and arena surfaces are reported to be strain rate dependant. It

169   was therefore hypothesised that any relationship between measurements from the OBST

170   compared to the GWTT and traction tester for the same surface, in particular measures of

171   rotational and longitudinal shear, would be non-linear and complex and would not be

172   expected to be well correlated. Also, even if a correlation between these devices was

173   observed on a particular surface it would not necessarily be applicable to other surfaces.

174   Therefore, the initial investigations using the GWTT and the other devices were performed

175   using two different types of surfaces.

176

177   **2 Methods**

178   The construction and measurements made by the traction tester and a first-generation OBST

179   have been previously described (Blundell et al., 2010; Peterson et al., 2008). In this work, we

180   give construction details of the GWTT, and describe the types of measurement that are made

181   by the traction tester, GWTT, and arena-surface modified OBST.   The three devices are

182   shown in Fig. 1.

183

184   **2.1 Equipment**

185   2.1.1 Glen Withy Torque Tester (GWTT)

186   The GWTT is an instrumented hoof design built into a support structure that can carry up to

187   100 kg mass and that has suitable attachments for a tractor or similar sized equipment to

188   move it easily. The support structure of the GWTT was based on a vertical central column

189   and horizontal cross member of 75 mm box section (see Figure 1). The central column houses

190   a 25 mm diameter main shaft that rotates on ball bearing races (47 mm outer diameter (o.d.))

191   at the top and bottom of the shaft. In addition, 2 ball bearing thrust races (50 mm o.d. at the

192   top and 100 mm o.d. at the bottom) carry the vertical thrust force. Attached to the bottom of

7

193   the main shaft is a housing that sandwiches a piezoelectric dynamometer (Kistler Instruments

194   Ltd. Hook, Hampshire, UK, model 9271A; model 9272 is the currently available equivalent),

195   through which applied vertical force and dynamic torque are applied and measured

196   respectively. A horseshoe is fixed to the bottom of the housing at the base. At the top of the

197   main shaft is a square fitting drive to which a two-ended handle can be secured when in use

198   to provide complementary torque. The amount of rotational twist is measured by a dial

199   indicator fitted to the square section. The housing of the central column supports adjustable

200   bars on both sides to allow easy attachment and removal of circular masses. A control box to

201   house the instrumentation is also secured to the central column. The horizontal cross member

202   is designed to be attached to the bottom two links of a type 1 three-point tractor implement

203   linkage. Attached to the cross member is a spring loaded linear potentiometer (Novotechnik,

204   Ostfildern, Germany, model TRS 100) with a foot at its base and this measures the vertical

205   displacement of the horseshoe into the surface as torque is applied. An attachment on the

206   column for the top tractor link of the three-point linkage is also provided (see supplementary

207   materials for assembly drawings). Once the GWTT is secured in the three-point-linkage

208   vertical stability can be maintained, but with sufficient slack to prevent resistance at the links

209   during testing which might otherwise influence the torque measurements. To obtain dynamic

210   measurements the equipment is lowered slowly to the ground on the three point linkage, once

211   slack against the links the handle is turned through a measured angle by the same operator

212   and then raised immediately after turning is complete. Typical hoof rotations during

213   locomotion are shown in Fig. 2, which highlights the point in the stance phase most relevant

214   to the operation of the equipment.

215

216   Three different masses were examined as part of the GWTT validation process. The mass of

217   the apparatus was 16 kg, which was used as a baseline measurement. Addition of a 30 kg

218   mass (total 46 kg) was selected as being equivalent to the mass used by the traction tester

219   (Blundell et al., 2010). Addition of a 100 kg mass (total 116 kg) was used which provided

220   approximately half the mass of a pony and one fifth the mass of a horse. Three turning angles

221   (40º, 90º, 140º) were selected to give an indication of the effect of turning by different

222   degrees on the variability of the data produced by the apparatus. The minimum angle of 40º

223   was chosen to represent the rotation of the horse's body about a grounded limb, for example

224   during a canter pirouette where the leading hind limb is in contact with the ground for almost

225   80% of the stride (Burns & Clayton, 1997). As maximum torque is normally produced prior

226   to shear failure, turning the GWTT through the maximum possible angle ensured that the

8

227   separate events of shear failure and maximum torque were most likely to be captured. While

228   the central column was able to be turned through an angle more than 140°, a maximum angle

229   of 140° was used. A rotation of the device of 90° provided an intermediate value. Turning

230   speed was estimated and reproduced through practice and repetition of the same operator.

231

232   The voltage signals from the dynamometer were amplified (Kistler Instruments Ltd. Hook,

233   Hampshire, UK, charge amplifier model 5073) and these, together with the linear

234   potentiometer signals were then converted to a digital signal (National Instruments UK,

235   Newbury, Berkshire, UK, A/D converter model NI USB-6210). All were sampled

236   simultaneously for 10 s at 100 Hz in Labview (National Instruments UK, Newbury,

237   Berkshire, UK). Peak torque (T_{max}), peak vertical displacement (D_{max}) and mean vertical force

238   (GRF_{mean}) were extracted from the digital data acquired using the device.

239

240   2.1.2 Traction Tester

241   The traction tester is a simple design that uses a steel rod attached to a circular, screw-on base

242   with a studded horseshoe on the underside of the base (Fig. 1). Three circular, 10 kg masses

243   each with a central hole are secured to the rod above the base. Two handles at the top of the

244   apparatus allow it to be lifted and dropped. The operator lifted the device to a height of 0.2 m

245   before releasing it, to allow the horseshoe to embed into the surface. Once the apparatus had

246   been dropped, a torque wrench was applied to the top of the rod and then was rotated until

247   shear failure of the surface occurred. The maximum value recorded (T_{maxTT}) on the torque

248   wrench prior to failure was tabulated for each trial. The same experienced researcher was

249   used throughout to reduce variability, consistent with general practice (Blundell et. al, 2010).

250

251   2.1.3 Orono Biomechanical Surface Tester (OBST)

252   The operation of this apparatus has been described previously (Peterson et al., 2008). For

253   these tests the hoof was dropped through a distance of 0.86 m down the rails which were at

254   an angle of 8° from the vertical. Temporal data from a tri-axial load cell (Kistler Instruments

255   Ltd. Hook, Hampshire, UK, type 9347C) and string potentiometer (Celesco, Chatsworth, CA,

256   USA, model PT5A) were recorded simultaneously (National Instruments UK, Newbury,

257   Berkshire, UK, A/D converter model NI USB-6210) for 2 s in Labview at 2000 Hz (National

258   Instruments UK, Newbury, Berkshire, UK). The files were converted to a suitable ASCII

259   format and then imported into Visual 3D. Landing force was determined from the vertical

260   component of force from the tri-axial load cell using a threshold of 50 N and peak vertical

9

261   force from the maximum value recorded ($GRFV_{max}$). Landing speed was derived from the

262   string potentiometer displacement data and the longitudinal component obtained using

263   trigonometry. Slip distance was then measured by double integration of the longitudinal

264   component of force, where the force was divided by mass prior to the first integration and

265   landing speed was used as a constant for the second integration. Slip distance during loading

266   (Slip) was then measured from landing to peak vertical force. The longitudinal force

267   component was rectified and the maximum value identified to obtain peak longitudinal force

268   ($GRFH_{max}$).

269

270   **2.2 Initial validation of GWTT measurements**

271   2.2.1 Procedure

272   A calibration measurement of the coefficient of friction of the GWTT shoe on black mild

273   steel plate was carried out in the laboratory using a calibrated 8 camera Qualisys Oqus system

274   capturing data at 100 Hz. Markers were attached at the top and bottom edge of a 1 m flat

275   black steel plate and four markers were attached to the underside of a shoe made for the

276   GWTT. Trials were captured as the shoe slid down the angled steel plate with the angle of the

277   plate being varied in small increments from trial to trial to provide data that included

278   speeding up, constant velocity and slowing down. Ten tests were recorded with the open end

279   facing up the slope and a further 10 tests with the open end facing down the slope. The angle

280   was varied for each trial. In addition, four repeated measurements of the angle required to

281   initiate movement of the shoe were recorded in four different orientations of the horse shoe;

282   front, back, left, right.

283

284   Measurement of the coefficient of friction of the GWTT shoe on black mild steel was carried

285   out in-situ using the GWTT and a flat black mild steel plate with steel grips welded to the

286   underside. This plate was firmly secured into an arena surface prior to testing. The GWTT

287   was loaded with 100 kg mass, lowered onto the steel plate and rotated slowly through 90° and

288   the load removed following turning. Eight repeated measurements were recorded.

289

290   2.2.2 Data Analysis

291   For the laboratory based measurements, markers on the flat plate and the shoe were tracked

292   and exported to Visual 3D. The angle of the plate was determined from the marker

293   coordinates and the shoe velocity during sliding was derived. Average acceleration was

294   calculated over the last third of the slope. The coefficient of friction was determined by

10

295 calculating the tangent of the angle. Static friction mean and standard deviation (s.d.) were

296 tabulated. Linear regression was used to determine the coefficient of friction value at zero

297 acceleration for sliding friction.

298

299 For *in-situ* measurements T_{max} and GRF_{mean} were extracted from the GWTT and the frictional

300 force calculated from the shoe dimensions. The coefficient of friction was calculated by

301 dividing the frictional force by GRF_{mean}. Mean and s.d. were calculated and results from the

302 *in-situ* test were compared to the laboratory sliding friction results.

303

304 **2.3 In-situ testing of GWTT, OBST and traction tester**

305 *2.3.1 Procedure*

306 Two artificial surfaces were used; a waxed sand and fibre surface and a non-waxed sand and

307 fibre surface. Each surface was tested using 5 repeats at 9 locations with each piece of

308 equipment separately (see Fig. 3). The order of testing of additional mass (0, 30 and 100 kg)

309 and turn angle (40°, 90° and 140°) was randomised.

310

311 A surface sample was also taken from each location. The top layer of surface was removed

312 and a minimum of 100 g of sub-surface was placed into a labelled plastic bag and sealed. To

313 evaluate moisture content 100 g of the surface from each sample was weighed out and placed

314 in a pre-weighed heat-proof tray that was baked in an oven at 38 °C for 48 h. The samples

315 were then re-weighed and the moisture content determined using ISO/TS 17892-1:2004.

316

317 Three temperature loggers (Gemini Data Loggers, Chichester, West Sussex, UK, model

318 Tinytag Talk 2) were utilised in the week prior to data collection. One was placed 100 mm

319 below the surface of the test track, one was placed on top of the surface, and the third was

320 placed above the surface to measure the air temperature. The loggers were programmed to

321 record temperature every 10 min. The mean temperature ± standard error in each position

322 was calculated for the week leading up to data acquisition. The measurements of moisture

323 for the unwaxed surface and temperature for the waxed surface are consistent with data

324 reported in the relevant literature (Bridge, Peterson, McIlwaith, Beaumont, 2010; Ratzlaff et

325 al., 1997). However, for consistency both temperature and moisture were measured for both

326 surfaces.

327

328 2.3.2 Data Analysis

11

329   Statistical analyses were performed in SPSS (IBM Corp., Armonk, NY, USA) with

330   significance set at $P<.05$. Data were screened for normality using a Kolmogorov-Smirnov

331   test. To identify the most appropriate protocol for use of the GWTT in relation to applied

332   load and turn angle, a 3 (mass) x 3 (turn angle) MANOVA was used with T_{max} and D_{max} as

333   dependant variables with Bonferroni post hoc tests on significant variables. To investigate

334   consistency of loading the limits of agreement between applied load and GRF_{mean} when

335   separated by mass and turn angle were determined (Bland & Altman, 1999). To evaluate the

336   relationship between measurements 1) on the same surfaces and 2) between surfaces made by

337   each piece of equipment, a partial correlation controlling for significant factors identified in

338   the MANOVA was used and 1) controlling for surface and 2) without controlling for surface.

339   Finally, a MANOVA was used for all measurements to compare the difference between the

340   two surfaces, with mass as a covariate. Stratified bootstrapping (1000 samples) was used on

341   all non-normally distributed measurements when conducting parametric tests.

342

3 Results

344   A typical raw data file is shown in Fig. 4 from the GWTT. Data were normally distributed for

345   D_{max}, T_{max} and *Slip.* All other data were not normally distributed. The coefficient of sliding

346   friction determined from the lab-based testing was 0.196±0.006 (mean±C.I.) (see Fig. 5) and

347   for *in-situ* testing was 0.173±0.021 (mean±s.d.) for the shoe on black steel plate. The

348   coefficient of static friction was 0.238±0.018 (mean±s.d.).

349

350   The moisture contents for the waxed surface and non-waxed surface were 5.1±2.11 % and

351   17.8±1.68 % respectively (mean ± s.d.). Air temperature, surface temperature and sub-surface

352   temperature in the week leading up to data collection measured in and above the waxed

353   surface were 19.5±0.1 ºC, 22.5±0.2 ºC, and 20.2±0.1 ºC respectively. Weather conditions

354   were considered to be temperate on the day of testing and there was no rainfall.

355

356   Mean ± s.d. results for T_{max} and D_{max} with respect to mass and turn angle for the GWTT, for

357   both surfaces combined, are shown in Table 1. A significant main effect ($P<.001$) of mass

358   was found in the model with significant differences for both T_{max} $F(2)=582.227$, $P<.001$ and

359   D_{max} $F(2)=6.754$, $P=.002$. No significant differences were found for turn angle and there was

360   no significant interaction between mass and turn angle.

361

12

362 The limits of agreement between GRF_{mean} and the applied load separated by mass are shown

363 in Fig. 6 together with the percentage of measurements that fell outside of ±1 s.d. limits for

364 each turn angle. The mean difference between measurements was -94.3±46.2, -75.0±106.3

365 and -23.1±75.5 N for 0, 30 and 100 kg masses respectively. A turn angle of 40° was most

366 often outside of the limits of agreement followed by 140°.

367

368 The relationship between measurements is shown in Table 2. When controlling for mass, a

369 weak negative relationship was found between D_{max} from the GWTT and T_{maxTT} from the

370 traction tester (R =-.257, P =.019). A weak positive relationship was found between D_{max} and

371 *Slip* (R =.234, P=.033). No other relationships between variables were found.

372

373 Measurements for all equipment (mean ± s.d.) are shown in Figure 7 separated by surface and

374 for the GWTT also separated by mass. A significant main effect (P<.001) was found for

375 surface with significant differences in T_{max} F(1)=12.38, P =.001, D_{max} F(1)=10.57, P=.002,

376 and $GRFV_{max}$ F(1)=15.37, P<.001. No other measurements were found to differ significantly

377 between surfaces.

378

379 **4 Discussion**

380 This study examined the capability of a newly developed piece of equipment, known as the

381 Glen Withy Torque Tester (GWTT), to measure rotational torque on equestrian arena

382 surfaces. The most appropriate protocols were compared over a range of applied loads and

383 turn angles and measurements made with the GWTT were compared to measurements from

384 existing equipment used to evaluate arena surfaces. It was hypothesised that any relationship

385 between measurements, in particular that between $GRFH_{max}$, slip and T_{max}, would be non-

386 linear and complex. When pooling the data a weak, but significant linear relationship was

387 found between the GWTT and OBST, which measure rotational compared to linear shear

388 resistance and where markedly different loads and loading rates are applied to the surface.

389 This relationship weakened when controlling for surface. These findings suggest that the

390 hypothesis might, in part, be cautiously rejected when comparing linear slip to vertical

391 displacement of the GWTT into the surface, providing a sufficient number of data points are

392 compared to account for location specific variability. The lack of correlation between other

393 measurements from the GWTT compared to the OBST supported the hypothesis.

394

13

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° turn angle provided the most consistent vertically applied load compared to the other two angles for all masses. For at 40° 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° 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° or 90° was more appropriate. One complete canter pirouette is usually completed in 6-8 strides, which suggests that the body will turn through 45-60° 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

14

429   GWTT is rigid, simulating a turn of a planted foot under a quasi-static load, so further work

430   is required to investigate it's applicability to the biomechanics of turning. The results can be

431   considered as promising though with respect to the magnitude of peak torque (T_{max}), since

432   they were comparable with those found by Chateau et al. (2013) in horses trotting in circles

433   on different surfaces.

434

435   The accuracy of the measurements from the GWTT were compared to standard laboratory

436   tests for static and sliding friction of the shoe on black mild steel. The coefficient of static

437   friction for steel on steel with an oxide coating was reported to be 0.27 and for sliding friction

438   with a greasy surface 0.09 - 0.19 (Engineers Handbook, 2006). These values are comparable

439   with the laboratory based test results and *in-situ* test results obtained in this study, suggesting

440   that the GWTT provides sufficient accuracy of measurement for friction and shear resistance

441   when loaded with a 100 kg mass.

442

443   Turning speed was subjectively controlled in the current study. As the surfaces tested are

444   strain rate dependant (Reiser et al., 2000), small differences in turning speed may have

445   influenced measurements from the GWTT. The GWTT has since been instrumented with an

446   angular potentiometer (see supplementary information), which will allow turning speed to be

447   taken into account in future work. This will also allow for a more detailed examination of

448   maximum torque and shear failure events using higher sampling frequencies.

449

450   **4.2 Relationships between measurements**

451   The relationship between the vertical displacement of the GWTT (D_{max}) and slip measured

452   from the OBST suggests that more slip would be expected on a surface where the top layer

453   deforms more under an applied load. Greater deformation is usually associated with more

454   particle movement as a consequence of large pore spaces and less angularity in sand shape

455   (Bridge, Mahaffey, Peterson, 2014). Moisture content, polymer binder and fibre content are

456   also relevant. The relationship was thought to be weak due to the viscoelastic nature of the

457   surfaces, particularly as the moisture content varied between surfaces and across locations.

458   The surface specific increase in T_{max} with an increase in D_{max} suggests that rotational torque

459   increases as the shoe is displaced further into the surface vertically, possibly due to increasing

460   forces from the surrounding substrate (Burn, 2006). This contradicts the relationship found

461   between D_{max} recorded with the GWTT and T_{maxTT} measured using the traction tester, which

462   suggests that surfaces with greater vertical deformation offer less traction. An explanation

15

463 may relate to the difference in function between the devices. The traction tester tended to be
464 pulled out from the surface, whereas the GWTT tended to "screw down" into the surface. The
465 traction measurement may therefore be indicative of the looseness of the cushion, rather than
466 the shear strength of the surface as a whole. The disputed reliability of the traction tester may
467 also have influenced these results (Twomey et al., 2011). The surface specific relationships
468 found for the OBST show the intrinsic link between the components of force from a dynamic
469 impact and data derived from forces, in this case slip.
470
471 The lack of a relationship between other measurements highlights the complexity of arena
472 surface functional properties and their measurement. The need for truly functional
473 measurements of arena surfaces is therefore clearly supported by these results. These
474 surfaces usually have a loose upper layer which allows motion of the hoof early in the
475 loading phase supported by an underlying firm layer. This stratification accentuates the non-
476 linear character of the materials since the initial stiffness of the surface is very low but it
477 increases with an increase in the load. This increase in stiffness as a function of loading
478 occurs in both vertical and horizontal directions. At the same time the strain rate sensitivity
479 of the loading in shear is characteristic of a porous material where flow of water or wax is
480 highly dependent on the loading rate (Bridge, Peterson, McIlwaith, 2011). This supports the
481 principle that the loading of the surface must represent the rate and load of the hoof for the
482 particular usage of the surface.
483
484 **4.3 Comparison of surface behaviour**
485 Differences between the waxed and non-waxed surfaces were detected by the GWTT and the
486 OBST, but not the traction tester. However, only the GWTT was able to detect significant
487 differences between the surfaces in relation to shear resistance characteristics.
488
489 The significantly higher torsional resistance measurements and the significantly lower
490 displacement measurements for the waxed surface when compared with those for the non-
491 waxed surface (all obtained using the GWTT), indicates that the waxed surface exhibits
492 greater shear resistance than the non-waxed surface. Although not significant, the reduction
493 in slip for the waxed surface also suggests that this surface has more grip. In baseball playing
494 surfaces with higher soil bulk density levels are associated with significantly increased linear
495 and rotational traction (Brosnan et al., 2009), which is thought to be due to a higher soil bulk
496 density causing greater resistance to the movement of the athlete's studs through the profile

16

497 (Brosnan et al., 2009). Less surface deformation together with reduced horizontal slip

498 distance was also found by Crevier-Denoix et al. (2013) when comparing horses cantering on

499 turf versus an all-weather waxed surface, but in this case the waxed surface had greater

500 deformation and slip. Chateau et al. (2009) also described an increased duration of the

501 braking phase on all-weather waxed sand compared to crushed sand. The wax component of

502 a surface may therefore be less of a determinant of shear resistance and grip than, for instance

503 the surface density.   Surface density did not, however, affect the traction values recorded on

504 synthetic equine surfaces using the traction tester (Holt et al. 2014), although these findings

505 may simply indicate that the equipment is not appropriate for such measurements rather than

506 indicating the lack of a relationship between traction and bulk density.

507

508 The similarity of $GRFH_{max}$ between surfaces was also somewhat surprising, as greater

509 maximum horizontal force has been measured on crushed sand in comparison to an all-

510 weather waxed track in trotters wearing a dynamometric horseshoe (Robin et al., 2009). In

511 addition, similarity in $GRFH_{max}$ infers similarity in shear resistance and slip, which was not

512 found. One of the confounding factors in the study of slip and shear resistance was the

513 damping ability of the surface. Crevier-Denoix et al. (2013) reported that waxed surfaces are

514 more effective in damping lower frequency concussion events. As such, indirect

515 measurements of slip may be difficult to interpret alone. Using the horizontal force

516 measurements to determine slip appears to be more sensitive to changes in surface type for

517 the OBST, rather than considering horizontal forces alone.

518

519 When comparing the range of measurements taken from each surface it was also apparent

520 that greater variability was consistently found on the non-waxed surface. Wax is reported to

521 improve surface consistency by reducing the effects of moisture (Bridge, Peterson,

522 McIlwaith, 2012), which was relatively high in the non-waxed surface on the test date. In

523 addition, the fibre type and distribution through the surface may have influenced variability,

524 as longer fibres were evident in the non-waxed surface.

525

526 Using the GWTT it was also possible to calculate the coefficient of sliding friction, which

527 was found to be 0.40 ±0.06 on the waxed surface and 0.37 ±0.11on a non-waxed surface.

528 These values are lower than the values of 0.585 to 0.741 reported when dragging cadaver

529 hooves across a dirt track (Clanton et al., 1991), and lower than for human sporting activities

530 (Shorten, Hudson, Himmelsbach, 2003). In the study by Clanton et al. (1991) the build up of

17

531 material in front of the hooves may have artificially increased the shear resistance. The

532 requirement for slide in equine activities is expected to be greater than in human activities.

533 Concrete, asphalt and rubber surfaces (smooth and patterned) have been shown to have a

534 static coefficient greater than 0.7, which limits the potential for hoof slip (McClinchey et al.

535 2004). Gustås et al. (2006) suggested that a high amount of friction during the hoof-surface

536 interaction increases vibration transients, resulting in mechanical stress to the structures of

537 the distal limb and possible injury, thus implying that a surface with a lower coefficient of

538 friction would be more favourable. Harder equine surfaces are commonly reported to have

539 increased grip, which does not support the $GRFV_{max}$ results compared to the results from the

540 GWTT. However, the $GRFV_{max}$ values are most likely to have been lower on the waxed

541 surface because the inclusion of a permavoid system in the sub-base has previously been

542 shown to significantly reduce peak vertical force using the OBST (Holt et al., 2014). This

543 highlights the need to use the OBST for measurement of the complete surface *in-situ*, as

544 many of the current measurement equipments are not capable of detecting differences below

545 the surface that the horse will experience.

546

547 **5 Conclusion**

548 In this study the GWTT was shown to be the only equipment tested capable of identifying

549 and measuring the difference in shear resistance of a waxed surface compared with a non-

550 waxed surface. This is an important consideration in equestrian sports for facilitating optimal

551 performance without compromising safety. Since the characteristics and performance of

552 arena surfaces are complex, it may be necessary to use more than one piece of equipment to

553 adequately characterise all the important functional properties. Based on the results presented

554 here data from the torque tester did not add significantly to the information provided by the

555 OBST and the GWTT. Future studies should carry out a more extensive evaluation of the

556 functional properties measured by the OBST and the GWTT to explore the complex

557 relationship between linear and rotational shear resistance under different loading conditions.

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744 **Figure Captions**
745

746 **Fig. 1: Photograph of: a) the Glen Withy torque tester (GWTT), b) the Orono**
747 **biomechanical surface tester (OBST) and c) the traction tester.**
748

749 **Fig.2: Typical rotational (R) and longitudinal (L) motions of the hoof during the hoof-**
750 **surface interaction viewed laterally a) footstrike, b) secondary impact, c) breakover**
751 **where pitch rotation and longitudinal sliding occurs. Frontal and solar views of d) roll**
752 **rotation, and e) yaw rotation which is most likely to occur during turning and are**
753 **usually accompanied by longitudinal and/or medio-lateral sliding. The GWTT**
754 **replicates motion and torque as shown in e).**
755

756 **Fig. 3: Plan of the data collection area used to test each of the two surfaces. Each mass**
757 **and each turn angle were tested at one of the locations. The order was randomised. The**
758 **testing areas were marked using flags and were 3 m $\times$ 4 m in size.**
759

760 **Fig. 4: A typical graph from the GWTT. The graph illustrates signals for GRF_{mean} (the**
761 **average of vertical GRF values over the time illustrated (kN)), D_{max} x 10 (mm), T_{max}**
762 **(Nm).**
763

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

24

766 **Fig. 6: Bland and Altman (1999) plot of the limits of agreement between GRF_{mean} from**

767 **the GWTT and the load applied ((machine mass + applied mass) x gravity) (N), a) 16 +**

768 **0 kg applied load, b) 16 + 30 applied load, c) 16 + 100 kg applied load. The dotted**

769 **horizontal lines show the limits of agreement at 1 standard deviation from the mean.**

770 **Data points outside of the dotted lines may be considered as inconsistencies in vertical**

771 **loading of the GWTT.**

772

773 **Fig. 7: Measured differences between surfaces for the GWTT: T_{max} (Nm), D_{max} x 10**

774 **(mm); the OBST: *Slip* (mm), $GRFH_{max}$ (kN), $GRFV_{max}$ (kN); and the traction tester:**

775 **T_{maxTT} (Nm). Error bars represent the standard deviation. * Significant differences**

776 **($P<.05$) were found for T_{max} and D_{max} and $GRFV_{max}$.**

777

778

25