Amateur football pitches: Mechanical properties of the natural ground and of different artificial turf infills and their biomechanical implications

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2   TITLE: Amateur football pitches: mechanical properties of the natural ground and of

3   different artificial turf infills and their biomechanical implications

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1 ## Abstract

2 Artificial turf is being used more and more often: it is more available for use, requires much

3 less maintenance and new products are able to comply with sport performance and athletes'

4 safety. The purpose of this paper is to compare the mechanical and biomechanical responses

5 of two different artificial turf infills (styrene butadiene rubber, from granulated vehicle tires,

6 and thermoplastic rubber granules) and to compare them to the performance of natural fields

7 where amateurs play (beaten earth, substantially).

8 Three mechanical parameters have been calculated from laboratory tests: energy storage,

9 energy losses and surface traction coefficient; results have been put in relationship with peak

10 accelerations recorded on an instrumented athlete, on the field.

11 The natural ground proved to be stiffer (-15% penetration depth for a given load), and with a

12 lower dynamic traction coefficient (-48%); the different kinds of infill showed significantly

13 different stiffnesses (varying by more than 23%) and damping behaviour (varying by more

14 than 31%). In running, peak vertical accelerations were lowest in the artificial ground with

15 thermoplastic rubber granules, while, in slalom, both artificial grounds produced higher

16 horizontal peak accelerations compared to the natural ground.

17 Results are discussed in terms of their implications for athletic performance and injury risk.

18

1. Introduction

New generation artificial turfs are having considerable success: the main advantages of artificial grounds compared to natural ones are greater availability for use, in terms of hours per day and meteorological conditions, and low maintenance. The third generation (3G) systems are characterized by long fibres in the carpet (40–65 mm), a relatively low tuft density, and, most of all, the presence of large quantities of infill in comparison to first or second generation products, with usually a sand layer at the base and crumbed rubber at the top; a shock-pad layer is often placed underneath the grass carpet. In his extensive review, Fleming (2011) reports technological advancement in artificial turf design, and summarizes performed researches, enlightening aspects which need to be further inquired; the same author demonstrates how different types of artificial turfs have been developed, so that it is now necessary to be able to classify them in order to optimize their performance. Three mechanical properties are surely relevant when considering ergonomics and injury risk (Nigg & Yeadon, 1987): energy storage, energy losses and friction of the surface (Nigg & Anton, 1995). Energy storage is directly related to the stiffness of the surface: Stefanyshyn and Nigg (2003) demonstrated that energy storage is related to both stiffness and to the square of maximum surface deformation; higher stiffness produces higher energy storage, lower deformation, but also higher impact forces. However impact forces are related to both stiffness and damping (i.e. internal energy losses) (Nigg & Liu, 1999); this last also determines the time required for ground vibrations to extinguish. Surface 'friction' should be more properly termed 'traction', as explained by Shorten, Hudson & Himmelsbach (2003): shoe-turf interaction is dominated by normal, rather than tangential contacts. Traction coefficient determines peak ground reaction force or moment (depending on the player's action), and ground rotational/translational stiffness; both quantities are responsible of athletes' performance and of non-contact injuries in sports, such as anterior cruciate ligament injury (Livesay, Reda & Nauman, 2006, Ekstrand & Nigg, 1989). Tests on artificial grounds can follow different objectives (Bartlett, James, Ford & Jennings-Temple, 2009): most

1 frequently, tests were finalized to sport performance assessment for certification procedures;

2 sometimes they were devoted to model/parameter identification (Guisasola, James, Stiles &

3 Dixon, 2010a; Guisasola, James, Llewellyn, Stiles & Dixon, 2010b).

4 Performance assessment of a specific product sample is directed at establishing whether it is

5 acceptable; for example, FIFA (International Federation of Football Associations) and UEFA

6 (Union of European Football Associations) have set up many criteria in order to assess shock

7 absorption ("Force Reduction", "Ball rebound", "Football pace" criteria), compliance

8 ("Vertical deformation" criterion), and friction ("Ball roll", "Rotational resistance", and

9 "Pendulum Test" criteria). In all these cases a specific input is given to the ground and the

10 output which is most selective for the physical property under investigation is measured

11 (Kolitzus, 2003): the need to specify acceptability criteria in the simplest and most

12 straightforward manner implies the acquisition of a limited number of data in well-confined

13 and easily repeatable experimental set up, however the mechanical behaviour is known to be

14 highly non-linear; therefore, surfaces with the same certification parameters may produce

15 quite different performances in real conditions.

16 This study aims to allow the identification of a three-parameter mechanical model in order to

17 allow a reliable description of the components and to support the analysis of player-surface

18 interaction with quantitative data: Stiles, James, Dixon and Guisasola (2009) well evidenced

19 in their work how sport surface design requires an integrated approach were both

20 biomechanical and mechanical aspects are inquired; this article considers both aspects: it

21 moves from the second ones, characterizing the mechanical performance of surfaces, and

22 successively inquires the biomechanical effects of measured parameters on an instrumented

23 athlete. This approach required to perform mechanical tests in laboratory, taking advantage

24 of the most refined equipment, while biomechanical tests were performed on the field.

25 Up to now, mechanical tests concerning natural and artificial turf have been performed both

26 on the field (Kirk et al., 2007; Clarke & Carré, 2010; Severn, Fleming, Clarke & Carré,

27 2011; Wannop, Luo & Stefanyshyn, 2012), and in laboratory (Clarke & Carré, 2010), with a

28 prevalence of the first ones, especially in the case of natural turf, as highlighted by Stiles,

4

1   Dixon and James (2006); laboratory mechanical tests performed by Guisasola et al. (2010a,

2   2010b) on the natural turf are unique as they supported the creation of a mechanical model

3   for the natural turf, considering possible variations in its composition, the effect of grass and

4   of progressive soil packing. Another parameter has been considered in the present work that

5   is turf infill: two different kinds of artificial turf infill have been here examined against their

6   most likely alternative for amateur football players in Italy, which are natural surfaces,

7   substantially made of beaten earth, with sporadic spots of grass.

8   Dealing with biomechanical tests or player-surface interaction, in literature these tests have

9   been more often performed in laboratory, typically on a force plate (Stiles, Dixon & James,

10   2006), obtaining the direct estimation of contact forces. Laboratories offer much more

11   reproducible testing conditions, simpler specimen care, but suffer from limitation of players'

12   behaviour, biases such as artificial light, and a limited range of motion, and tests repetition

13   on the same surface area (Kirk et al., 2007); a different approach has been followed by other

14   authors and in this paper, having instrumented an athlete, and acquiring data on the field:

15   Ford et al., 2006 acquired foot pressure distribution, Kirk et al., 2007 performed high-speed

16   video analysis; ankle joint acceleration history has been here acquired; the experimental

17   results coming from mechanical tests have been so put in relationship with players' peak

18   accelerations at the ankle. Measurements on the field are prone to larger variability due to

19   climatic conditions and personalised human subject behaviour, but offer the chance to

20   exactly reproduce kinetic and kinematic data.

21   Quantitative data on artificial turf used in third generation soccer pitches have seldom been

22   reported extensively, neither has the influence of different grass infill on athletes peak joint

23   acceleration been highlighted : more often, studies concerning differences of injury rate in

24   relation to playing surface have been published (Ekstrand & Nigg, 1989; Orchard, 2002) or

25   concerning performance assessment (Bartlett et al., 2009); besides, in most studies the

26   effects of stiffness and damping are mixed in one only parameter which determines 'peak

27   impact force' or 'surface hardness'.

2. Methods

2.1 Turf Samples

Three samples have been analysed: two samples are appositely produced trays (40x40 cm) of third generation artificial turf with different synthetic infill (Table 1) provided by the installers of the outdoor surfaces examined in biomechanical tests; the installed surfaces have been homologated according to the Italian Amateur's Football League; neither sample includes shockpads. The third sample was carefully cut from an outdoor amateur playing surface, which had been installed at least five years before being tested: it is a firm ground, consisting of pressed earth, with sporadic spots of grass (80% sand with 0.2-2 mm granulometry; 20% peat moss; 11% volumetric water content); it was enclosed in an apposite tray, sized 40x40 cm; a clod depth of 30 cm was chosen, considerably greater than the depth of the volume stressed and strained in an appreciable way (Schmertmann, Hartmann & Brown 1978).

Each sample was replicated 6 times, in order to take into account inter-specimen variability.

All samples were enveloped with plastic film, and stored in a climatized room at 20°C, 50% humidity.

2.2 Mechanical tests

All tests were performed on a Schenck RSA 100 kN electromechanical test machine (by Schenck Trebel Corporation, USA).

2.2.1 Energy storage and energy losses

Energy storage capability and energy losses were assessed examining the pattern of load vs. displacement for five consecutive cycles; the testing machine was equipped with a 70 mm diameter aluminium disk (Figure 1), like the artificial foot used in the "Force reduction test" (Kolitzus, 2003); actually, soccer players wear studded shoes and UEFA has introduced a test with studs (UEFA, 2003). However, Durà (2003) has demonstrated that, with regard to axial testing, the results obtained differ little from those of the flat foot. Five measurement

1   areas were identified on each clod. Three different maximum loads were considered: 1000 N

2   (compression), 2000 N and 3000 N; these loads are thought to well represent the vertical

3   dynamical load range for an 80 Kg subject: Ozkaya and Nordin (1999) estimated the peak

4   vertical ground reaction force) in running is equal to 2.8 body weight; according to Severn et

5   al. (2011) the same force may be in the range of 2 to 3 body weight, respectively for

6   movements such as cutting and stopping. Each test was repeated under three different

7   velocities: 0.33 mm/s, 0.67 mm/s, and 1 mm/s; these speeds are certainly far below the peak

8   impact speed in foot landing phase; however, three aspects must be considered: first, during

9   the impact the speed reduces from its initial value to zero, while the force varies from zero to

10 its peak, therefore, having considered peak force coupled to low speed should not be such an

11 unrealistic condition. The second aspect is that it is true that the loading rate has a consistent

12 and demonstrated effect on rubber compliance, however this influence is not so dramatic

13 unless very high strain rate are reached: referring to styrene butadiene rubber (Brown et al.,

14 2010), results for strain rate ranging for 0.001/s to 0.1 s show little variation, while results

15 for strain rate above 1000/s are significantly different; damping is more sensitive to loading

16 rate than stiffness. Finally, this article is focused on the comparison between different pitches

17 performances and quasi-static tests could give some useful indications in this sense.

18 Nonetheless, the study of higher rate would certainly give further information, and is a limit

19 of this work due to the limited capabilities of the employed testing machine.

20 The final aim was to assess stiffness and damping behaviour as a function of load amplitude

21 and velocity.

22 Stiffness was evaluated considering:

23   -   an average curve, obtained from loading and unloading curves, for each cycle

24   (Figure 1, top), this curve was interpolated with an exponential function (Figure 1,

25   bottom) whose exponent (m) is directly related to stiffness;

26   -   the straight line which connects the terminal points, with coefficient K_{sec};

27   -   the penetration depth of 3000 N load (s_3000).

1   Damping was estimated considering the hysteresis loop area (Figure 2, 'Dissipated Energy'),

2   normalized with reference to the input elastic energy (Figure 2, the area under the

3   interpolated curve), giving specific damping (Bert, 1973) which is an intrinsic physical

4   property of the sample.

5 2.2.2   Traction

6   The experimental set up for dynamic traction measurement is shown in Figure 3; it is a three-

7   legged structure which can translate across a flat surface, being pulled by the testing

8   machine, while the 'artificial foot' (the 70 mm disk already used for stiffness and damping

9   assessment) is dragged on the clod surface; this last can be vertically loaded by means of

10   static weights: the weight was increased in 100 N steps, from 144 N to 844 N, and two

11   different translation speeds were considered: low (0.67 mm/s), and high (8.33 mm/s). We

12   chose to use a smooth plate instead of a studded one (Willcock, Meyer, Powell, Fouty &

13   Haut, 2009) in order to obtain results as general as possible, related to the transversal

14   strength of the surface and not confined to one specific stud shape or pattern; besides, results

15   obtained on a given studded plate hold only for a specific frontal stud/flat metal base area

16   ratio, whenever full studs penetration has been achieved (Severn et al., 2011). Accordingly,

17   the authors chose to use a horizontal force instead of a torque moment, in order to produce a

18   stress distribution as uniform as possible.

19   According to Clarke and Carrè (2010), the pulling force (F_t) is produced by two main effects:

20   the first one is the tangential force exerted by the ground against the penetrated area of the

21   stud, while the second effect develops when the 'fully penetrated studs condition' has been

22   reached: in this case, the sole produces a compression of the soil located around the studs,

23   increasing its stress.

24   These phenomena can be so modelled for one single stud:

25
$$F_t = \sigma \cdot A_f = \sigma \cdot L_{eq} \cdot PD = \sigma \cdot L_{eq} \cdot \chi \cdot \frac{F_a}{A_t} = \sigma \cdot \chi \cdot \frac{L_{eq}}{A_t} F_a \qquad (1)$$

1   Where σ represents the traction stress between the soil and the stud and A_f is the frontal area

2   of the stud, and L_{eq} is an equivalent transversal length: it produces the transversal area A_t

3   when multiplied by the penetration depth. The penetration depth is proportional (through χ)

4   to the axial stress level on the ground, calculated from the axial force F_a, divided by the stud

5   transversal section (A_t); traction stress σ can change when the studs fully penetrate.

6   In the case of a cylindrical stud (same geometry as the flat foot):

7    $$F_t = \sigma\chi\frac{D}{\pi \cdot \frac{D^2}{4}} = \sigma\chi\frac{4}{\pi D}F_a \qquad\qquad (1a)$$

8   The tangential force is so inversely proportional to the diameter.

9   This experimental set up with the flat foot cannot simulate the second effect (the full

10   penetration condition is never achieved) or secondary effects produced by specific stud

11   shapes such as impingement or compression.

12   Since the traction force remains proportional to the axial force F_a, a traction coefficient c can

13   be introduced, according to the following formula:

14   $$c = \frac{F_t}{F_a} = \frac{4\sigma\chi}{\pi D} \qquad\qquad (2)$$

15   This coefficient depends on the stud geometry and on soil compaction (through σ); therefore

16   comparisons among surfaces must be obviously performed using the same stud geometry (or

17   the same boots), and reporting the infill bulk density (Severn et al., 2011).

18   A typical result is plotted in Figure 3: in spite of differences in the experimental set-up, the

19   pattern is similar to the one reported by other authors (Livesay et al., 2006): there is an initial

20   steep increase (a sort of breakaway region), followed by a smoother increase of force with

21   additional displacement; a peak force is then reached, followed by relative slippage between

22   the plate and the tested surface. The arrow marks the point where the slope

23   load/displacement reaches a plateau; this was used as reference point for the dynamic

24   traction coefficient estimation. The suitability of considering this value is being debated in

25   literature because its respective displacement (over 40 mm) is far beyond the typical foot

9

1 displacement in football playing (about 20 mm), as demonstrated by Kirk et al., (2007);

2 consequently, some authors suggest considering the tangential force corresponding to 20 mm

3 displacement; in the opinion of the authors, further experimentation is required in order to

4 demonstrate if it is this displacement or the traction force itself that would remain constant

5 on different pitches; the second hypothesis can be supported considering that the traction

6 force represents the reaction required by an athlete for sprinting, cutting, etc. Besides, a

7 different approach should be followed according to what aspects are being considered: if

8 injury is the major concern, the 'peak force approach' can be adequate because it measures

9 the maximum input force which can be produced by a surface; if wear or fatigue is being

10 inquired, the most recurring activities should be taken into account and therefore the 'fixed

11 displacement force' or, even better, the slope of Force/Displacement curve should be taken

12 into account. In this work, the authors decided to follow the 'peak force approach', being

13 most interested on injury probability, and taking advantage of the broad literature which

14 follows this same approach.

15 Once the traction coefficient has been estimated for the flat foot, the peak torque, which is

16 the most often reported datum in literature, can be estimated for different contact surfaces

17 (studded plates), on the basis of the simplified assumption that the sole is not in full contact

18 with the ground:

19
$$M_{peak} = \sum_{i=1}^{n} F_{t,i} \cdot r_i = \sum_{i=1}^{n} \eta_i \cdot (\sigma\chi) \cdot \frac{L_{eq,i}}{A_{t,i}} F_{a,i} \cdot r_i = \sum_{i=1}^{n} \eta_i \cdot \left(\frac{4c}{\pi D}\right) \cdot \frac{L_{eq,i}}{A_{t,i}} F_{a,i} \cdot r_i \qquad (3)$$

20
$$F_{a,i} = \frac{F_a}{n};\qquad\qquad\qquad\qquad\qquad\qquad\qquad (4)$$

21 Where:

22 M_{peak} is the peak torque; n is the number of studs; i is an index to refer to the i_{th} stud; r_i is the

23 distance of the i_{th} stud from the rotation axis (the assumption was made that the whole stud

24 cross-sectional area can be concentrated in one point); η_i is a shape coefficient which must

25 be determined experimentally whenever the stud shape is far from cylindrical.

10

1 Equation (3) can be simplified whenever all studs are identical, cylindrical and located at the

2 same distance from the centre of rotation (3a):

3
$$M_{peak} = \left(\frac{4c}{\pi D} \right) \cdot \frac{L_{eq,i}}{A_{t,i}} F_a \cdot r_i \qquad (3a)$$

4 This formula is confirmed by the experimental finding of Severn et al. (2011) who

5 demonstrated how a doubled radial distance produces a doubled torque moment.

6 The interesting aspect is that the torsional moment M_{peak} is related to the coefficient of

7 traction c through geometrical constants which do not depend on the considered soil;

8 therefore comparative data obtained in laboratory hold also for tests on the field, with the

9 studded plate or with boots.

10 The test samples were reconditioned between repeated tests, using a small rake to

11 redistribute the rubber granules evenly; the sample was moved between trials to ensure a

12 'fresh' region of the playing surface was examined during each test; consecutive tests were

13 performed along orthogonal directions.

14 2.2.3   Data analysis

15 With regard to the statistical analysis of data, the Friedman test for paired data was used in

16 order to assess the influence of different parameters such as the vertical load or the speed on

17 the measured variable: this is a non-parametric that compares three or more paired groups.

18 The same test was used to assess whether the three clods behaved in a significantly different

19 way; when the null hypothesis was rejected, Bonferroni post-hoc multiple comparison test

20 was performed and the classifiers were compared to each other.

21 ## 2.3 Biomechanical tests

22 Eight athletes were instrumented by means of 3 capacitive accelerometers (Lafortune, 1991;

23 Auvinet et al., 2002), 20g range, 350 Hz natural frequency (PCB 3801D1FB20G, PCB

24 Piezotronics, USA). Athletes were informed of research purposes of these tests which have

25 been approved by their society ethics committee; their weight ranged from 72 to 85 kg; their

26 height ranged from 1.73 to 1.91 m, and they were aged between 23 and 28. They all wore the

1   same shoe model, designed for playing on natural grounds, with moulded polymer studs

2   around the perimeter of the shoe sole, and with smaller traction elements in the centre of the

3   sole.

4   The accelerometers were placed on three orthogonal faces of a cube; this cube has been

5   glued on a metallic plate which has been bound to the athletes' tibia through Velcro straps,

6   being placed in correspondence of the ankle (fig. 4). The accelerometers were oriented in

7   accordance to tibial anatomical axes.

8   Sampling frequency was set at 1 kHz.

9   Athletes were asked to perform typical football actions such as:

10 -   straight running at 168 bpm (beats per minute, paced by a digital metronome);

11 -   straight running at 200 bpm (beats per minute);

12 -   tight slalom (1 gate per 225 cm);

13 -   zig-zag running (+45°,-45°).

14 Each athlete performed all tests on three different kinds of surfaces, corresponding to the

15 three samples considered in mechanical tests: artificial turf with thermoplastic rubber

16 granules infill, natural turf, artificial turf with styrene butadiene rubber infill, in this order;

17 they rested for at least thirty minutes between successive trials. Both artificial surfaces have

18 been built by the same installer who provided the laboratory sample, guaranteeing the

19 sample was identical to the installed pitch. For what concerns the natural surface, the sample

20 has been cut from the surface itself and therefore has the same composition. Differences

21 between laboratory and biomechanical tests temperature were below 3°C; the humidity of

22 the natural sample (11% water content) was kept constant during laboratory tests, and

23 biomechanical tests on the natural field were performed in a short lag of time (few days)

24 were no precipitation took place and no maintenance watering was performed since

25 specimen cutting; the natural pitch was quite dry since the beginning, therefore no significant

26 evaporation is likely to have taken place. These surfaces belonged to pitches for amateur

27 soccer playing, belonging to the city of XXX, XXX.

28 The following data were obtained from acceleration histories (figure 5):

- PPZ, NPZ: positive and negative peak acceleration along the vertical axis, respectively;
- PHOR –peak of the horizontal acceleration obtained from the composition of the medial-lateral and antero-posterior accelerations.

Each test was repeated over ten times per athlete on different days, in order to validate the experimental procedure, and to obtain an estimation of measurement standard error.

2.3.1   Data analysis

With regard to the statistical analysis of data, the Friedman test for paired data was used in order to assess if the accelerations measured for the same athlete on different surfaces were significant. When the null hypothesis was rejected, Bonferroni post-hoc multiple comparison test was performed and the classifiers were compared to each other. The significance level has been fixed at 5% for all statistical tests.

3. Results

The most significant results are reported in Table 2 and discussed below; they refer to energy storage, energy losses and traction.

3.1 Energy storage

Data describing energy storage showed high variability (these are original data, not averaged yet), which is likely due to the spatial unevenness of the ground itself: when the tests were repeated on the same location, variability was greatly reduced.

Velocity was not found to have an influence on clod stiffness, at least for the explored velocity range.

The behaviour of the three clods examined proved to be significantly different, even though the variance of results is high ($p < 10^{-5}$, Friedman test for paired data), the difference between whatever pair is significant (Bonferroni test, $p < 0.05$): mechanical behaviour of earth is stiffer than artificial turf with thermoplastic compound infill and the latter is stiffer than artificial turf with styrene butadiene rubber infill (Figure 6).

3.2 Energy losses

The results obtained for specific damping showed better repeatability (Table 2).

Load speed was found to affect the results (p<0.02, Friedman test for paired data): moving from 0.33 mm/s to 0.67 mm/s, the specific damping decreased 5-16%.

Also load amplitude influenced the results (p<0.06, Friedman test for paired data): moving from –1000 N to –3000 N, specific damping increased 9-16%.

The behaviour of the three clods examined is significantly different (p<$2 \cdot 10^{-3}$, Friedman test for paired data); while natural ground and artificial turf with thermoplastic infill behave similarly, the specific damping coefficient of artificial ground with styrene butadiene rubber infill is 39% lower (Bonferroni test, p<$3 \cdot 10^{-6}$) (Figure 6).

3.3 Traction

Regarding traction, the artificial turf with styrene butadiene rubber infill produced the least variability, compared to artificial turf with thermoplastic infill and to natural ground: in both cases, the loaded artificial foot showed a tendency to wedge and, in effect, it furrowed uneven ground surfaces.

Neither the speed nor the applied vertical load exerts an influence on the dynamic traction coefficient even though both were varied over an extensive range; this finding justified traction force normalization with respect to the applied axial force (Equation 1).

The behaviour of the three clods examined is significantly different (p<$2 \cdot 10^{-4}$, Friedman test for paired data); in detail, the artificial ground with thermoplastic infill show the highest traction coefficient (0.85), while the natural ground shows the lowest one (0.36) and has a significantly different performance (Bonferroni test, p<0.05) (Figure 7).

3.4 Biomechanical tests

Results from biomechanical tests can be divided in two groups, according to the direction of the main acceleration: in straight running, the vertical acceleration is prevailing, while in slalom and zig-zag running, the highest acceleration component is horizontal.

14

1   Main Vertical acceleration

2   Considering 168 bpm running, the artificial ground with thermoplastic infill produced the

3   lowest vertical accelerations (p<0.001, fig. 8), while the natural ground and the artificial

4   ground with styrene butadiene rubber infill behaved similarly. Data coming from 200 bpm

5   running confirmed the first observation, while the artificial turf with styrene butadiene

6   rubber infill produced higher accelerations compared to the natural one (p<0.006).

7   Main horizontal acceleration

8   Zig zag tests produced results with very high variability and therefore were not considered in

9   the following, slalom tests produced much more repeatable results. The differences between

10   whatever pair of surfaces were relevant (Bonferroni test, p<0.03); in detail, the natural turf

11   produced the smallest peak horizontal accelerations; the artificial turf with styrene butadiene

12   rubber infill showed intermediate values, the artificial turf with thermoplastic infill produced

13   the highest horizontal accelerations (fig. 9).

14

15   One more statistical analysis was performed in order to compare 168 bpm running results

16   variance on different surfaces by means of statistical F-Test: the artificial ground with

17   thermoplastic infill produced a significantly lower variability of results, compared to the

18   natural ground (p<0.001), and to the other artificial ground (p<0.002).

19   4. Discussion

20   This article is an application of ''Orthopaedic sport biomechanics'', as explained by Chan et

21   al. (2008), where an extensive review is reported illustrating the role of biomechanics in

22   preventing and managing sports injury. According to these authors, biomechanics has three

23   main roles: injury prevention, immediate evaluation of treatment, and long-term outcome

24   evaluation; this work addresses the first issue. The inquiry moves from the identification of

25   main mechanical risk factors, specifically related to the playing surface, according to

26   existing literature: the stiffness, internal damping and traction properties (Nigg & Yeadon,

1 1987; Ekstrand & Nigg, 1989; Nigg & Anton, 1995; Wright, Neptune, Van Der Bogert &

2 Nigg, 1998; Nigg & Liu, 1999; Livesay, Reda & Nauman, 2006).

3 A peculiarity of the present work is that energy storage, internal damping, and traction

4 properties were assessed in the laboratory using specific tests; therefore temperature and

5 humidity could be standardized: other authors emphasized the effect of both factors on

6 surface behaviour (Orchard, 2002); a limitation of this study is that at the moment only one

7 temperature/humidity condition has been considered. Works by Guisasola et al. (2010a,

8 2010b) can allow inferring changes in the natural soil behaviour produced by different soil

9 composition, different water content, or different soil packing.

10 The stiffness and the energy absorption properties of playing surfaces were evaluated by

11 means of two completely independent physical properties: stiffness and specific damping. It

12 should be emphasized that, given the applied force, a stiffer surface can show a higher

13 specific damping because it produces a lower elastic energy income and specific damping

14 relates the dissipated energy to the income elastic energy.

15 The artificial ground with thermoplastic infill resulted to produce lower peak vertical

16 accelerations compared to the natural ground and to the artificial ground with styrene

17 butadiene rubber infill, these last appeared to behave similarly at 168 bpm running; this

18 results could be surprising, considered that mechanical tests demonstrated how styrene

19 butadiene rubber infill stiffness was the lowest, and close to thermoplastic infill stiffness,

20 while the natural ground stiffness was by far the highest. However, it should be noticed how

21 artificial turf stiffness values compare well with other running tracks (Stafilidis &

22 Arampatzis, 2007), and it has been widely demonstrated how athletes are able to adjust the

23 stiffness of their legs to compensate for even greater variations in ground stiffness, leading to

24 peak loads (Feehery, 1986) and sprinting performances (Stafilidis & Arampatzis, 2007)

25 which are weakly related to ground stiffness. Therefore, when stiffness values are similar,

26 damping is the key parameters and this explains why thermoplastic infill produced lower

27 peak vertical accelerations compared to styrene butadiene rubber infill; the natural turf has

28 shown the highest damping, but its stiffness is also noticeably higher and this is the reason

1 why its peak acceleration remains higher than thermoplastic infill one, and close or lower

2 than the peak acceleration of styrene butadiene rubber one, respectively at 168 bmp and 200

3 bpm. This discussion demonstrates how the obtained results are plausible; however it should

4 be confirmed quantitatively, by further tests; in particular it would be useful, when testing

5 outdoor pitches, to perform also tests where the human factor is not involved, making use of

6 mechanical devices: this would allow to validate laboratory tests and to isolate the dynamic

7 contribution of the ground only.

8 Referring to vertical loads and joint injury risk, the artificial turf with thermoplastic infill can

9 be considered the safest; dealing with fatigue, being true that athletes are able to adjust the

10 stiffness of their legs to compensate for greater variations in ground stiffness, it can be

11 postulated that lower ground compliances are associated to the need of higher leg stiffness,

12 and this implies more fatigue and energy expenditure; a proof is that tiredness is one of the

13 aspects where artificial turf gained the lowest score, compared to natural turf, as reported in a

14 previous survey on amateur players (Zanetti, 2009). Another significant issue related to

15 surface stiffness is foot stability (Fong, Hong, Chan, Yung & Chan 2008a); as stated by other

16 authors, this issue deserves further specific attention (Steffen, Andersen & Bahr, 2007):

17 further insight could be reached analysing pressure distribution through specific insoles

18 (Fong et al., 2008b). As a general trend, even if the peak load does not vary, the same

19 equation does not hold for tendons and ligaments which are more stressed by a harder

20 ground (Wright et al., 1998), but even the hardest surface, i.e. natural ground, did not

21 produce alarming values from this point of view.

22 Dealing with traction tests, the experimental set up has been validated through two further

23 tests where the artificial foot slid on a steel surface with or without lubricant. These tests

24 have resulted in a friction coefficient of 0.16 for the artificial foot sliding on a steel surface

25 without lubricant, and 0.14 for the lubricated contact; both results compare favourably with

26 the literature (Blau, 1992); consequently, the measurement system used here was judged to

27 be reliable from a mechanical point of view. The results reported are also compatible with

28 the 21 to 39 Nm reported by other authors for the peak torque under a compressive load of

1 333 N (Livesay et al., 2006), considering the simplified Equation (3a). The simplified

2 experimental set up with a cylindrical flat foot instead of a studded one, allows to appreciate

3 the traction force produced by the soil traction stress resistance, while the 'fully penetrated

4 stud' condition is never reached, and the increased benefit of soil compaction produced in

5 this condition cannot be measured. An analytical demonstration that comparative results

6 obtained with this flat foot hold also for studded plated or boots has been given along with

7 coefficients which take into account stud geometry.

8 Traction properties of both artificial grounds were found to be higher than that of the natural

9 ground; a similar finding was reported by authors who compared peak torques reached on

10 natural grass and on other third generation surfaces with rubber infill (Livesay et al., 2006;

11 Willwock et al., 2009). Other authors (Guisasola et al., 2010b) analysed different samples

12 made of natural earth and demonstrated that other soils (e.g. a Clay Loam soil or a soil

13 having higher water content) produce even lower traction forces than the densely packed

14 sandy sample here examined.

15 Traction property is quite relevant because it can be put in relationship with peak tangential

16 athlete-surface forces: this work has demonstrated that higher traction coefficients

17 correspond to higher peak horizontal accelerations, as in the case of artificial grounds, and,

18 particularly, of the artificial turf with thermoplastic infill. Traction can be directly related to

19 both performance and risk of foot plant injuries such as anterior cruciate ligament tears

20 (Ekstrand & Nigg, 1989): soccer is characterized by sprinting, stopping, cutting and pivoting

21 situations, where shoe-surface relations are essential and traction must be within an optimal

22 range, arriving at a compromise between performance and protection. The ratio of traction

23 coefficient of artificial surfaces to the traction coefficient of the natural ground (2.36:1 for

24 thermoplastic rubber, 1.92:1 for styrene butadiene rubber, Table 2) is a point of concern

25 because it could be only partially compensated, matching the artificial surfaces to turf shoes:

26 in fact, these shoes produce a peak moment torque which ranges from 1/1.66 to 1/1.38, the

27 peak torque reached by conventional soccer shoes on the same ground (Willwock et al.,

28 2009).

Interestingly, there is no effect of the relative velocity between the artificial foot and the turf surface; this result agrees with findings of previous researchers who examined rotational friction (Andreasson, Lindenberger, Renstrom & Peterson, 1986) and suggests that play speed should not be relevant.

5. Conclusions

Many aspects concerning the performance of modern infill artificial surfaces still need investigation. The present research characterized three specific mechanical aspects: energy-storage capability, energy losses, and traction, on three different playing surfaces: artificial turf with styrene butadiene rubber infill, artificial turf with thermoplastic infill, natural ground. A peculiarity of this study is that amateurs' playing surfaces were examined, i.e. real natural surfaces, substantially consisting of pressed earth without grass.

Traction property was evaluated through a conventional test in order to obtain surface-specific results, which are not dependent on shoe-stiffness, stud pattern or stud shape (Livesay et al., 2006).

The natural ground and both artificial surfaces showed different performances from the point of view of energy storage: the natural ground was by far the stiffest surface, the turf with styrene butadiene rubber infill was softer (-72% secant stiffness) as was also the turf with thermoplastic infill (-63% secant stiffness).

The natural ground and the turf with thermoplastic infill behave alike from the point of view of specific damping, while the turf with styrene butadiene rubber infill is less dissipative (-39% specific damping).

Energy storage and damping capabilities of surfaces play a role in determining peak vertical acceleration in running: athletes have the capability of adapting their own leg stiffness to ground behaviour; from biomechanical tests peak vertical accelerations in running have resulted to be equal between the artificial ground with styrene butadiene rubber infill and the natural ground or higher in the first one, depending on running speed, while the artificial ground with thermoplastic infill always produced the smallest peak vertical accelerations.

Both artificial surfaces are more critical than the natural one from the point of view of traction (+136% and +92% traction coefficient for thermoplastic and styrene butadiene rubber, respectively), and this produced higher peak horizontal accelerations in slalom tests, especially for the artificial ground with thermoplastic infill; this last however gave a more consistent performance.

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Figure Captions

3 Figure 1 Vertical loading-unloading test: repeated cycles with linear scales (upper figure):

4 after few cycles, load displacement curves become repeatable and overlay; one of

5 stabilised cycles, interpolated with a line in a semi-logarithmic plane (lower

6 figure).

7 Figure 2 Accumulated elastic energy and dissipated energy for one loading cycle

8 Figure 3 Friction test: Force/Displacement pattern

9 Figure 4 Experimental set up for ankle acceleration measurement

10 Figure 5 Acceleration history during a 200 bpm running

11 Figure 6 3000 N penetration depth and damping of the three clods

12 Figure 7 Friction of the three clods

13 Figure 8 Peak vertical acceleration on the three pitches (168 bmp and 200 bpm running)

14 Figure 9 Peak horizontal acceleration on the three pitches (slalom test)

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1   Table 1. Artificial Turf Samples description

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		Specimen #1	Specimen #2
Grass	Material	Monofibre Polyethylene	Monofibre Polyethylene
	Weight/Length [dtex]	11100	11514
	Points/Area [pt/m^2]	10625	8400
	Pile Length [mm]	60	60
Sand	Granulometry [mm]	0.4-0.8	0.4-0.8
	Weight/Area [kg/m^2]	12	18
Synthetic Infill	Material	Thermoplastic compound Rubber	Styrene Butadiene Rubber
	Granulometry [mm]	0.5-2.0	0.8-2.0
	Weight/Area [kg/m^2]	15	17
	Shape	Lenticular	Prismatic

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Table 2. Mechanical properties of different clods and differences between artificial and

natural clod properties

	Energy storage			Internal Energy Losses	Traction*
	m [1/m]	K_{sec} [kN/m]	s_3000* [mm]	Ψ	f
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Earth	1840 (175)	1034 (100)	3.2 (0.25)	0.71 (0.027)	0.36 (0.018)
TR*	680 (18)	381 (11)	7.9 (0.24)	0.62 (0.010)	0.85 (0.015)
*Δ** [%]*	*-63%*	*-63%*	*+147%*	*-12.68%*	*+136%*
SBR*	520 (10)	291 (5)	10.3 (0.19)	0.43 (0.010)	0.69 (0.015)
*Δ** [%]*	*-72%*	*-72%*	*+222%*	*-39%*	*+92%*

4   * Termoplastic Rubber Infill

5   ** Percentage differences are calculated with reference to the natural ground

6   *** Styrene Butadiene Rubber Infill

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