THE PHYSICS OF SPORTS SURFACE TESTING – FORCE REDUCTION

INTRODUCTION

This document has been developed with two purposes in mind. First, it is intended to help those in the sports surface market better understand the physics used while conducting performance testing of sports surfaces. Those seeking to better understand the differences between different levels of performance may find this very simplistic view helpful. Secondly, it has been developed with the idea of showing that physics is not simply some esoteric concept studied and only used by rocket scientists. Hopefully it can show that physics can help to understand the world and that its application need not be limited to quantum mechanics or a unified theory.

Force Reduction, or shock absorption as a property of a sports surface was introduced as a concept in DIN 18032-2 sometime in the mid 1980's. Since then a few minor modifications have been made, and a number of standardization and governing bodies have adopted the test method. It is now used in testing indoor courts (wood and synthetic), running tracks, dance floors, and a variation is used on artificial turf fields. This publication provides an introduction to the physics behind force reduction or shock absorption testing in many common standards (EN 14904, DIN 18032-2, ASTM F2772, ASTM F2157, ANSI E1.26, FIFA, ISTA, and FIFA just to name a few).

Note: The term 'Shock Absorption' is sometimes applied to this property (in fact this the term used EN 14904), but I think that term does not reflect what is being measured or reported. Shock Absorption is traditionally viewed as the ability of a system to absorb energy. This test does not measure energy so in my opinion, the proper term is actually Force Reduction. The rest of this paper will use 'force reduction' exclusively when referring to this property. There is a new standard in use (FIFA Rules 2012) that does measure energy return. The physics behind the two systems used to measure force reduction is similar and can be applied to either method. The systems used in this publication are too simple to be used to look at energy return or shock absorption.

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PREFACE

Today, scientists and engineers have virtually unlimited computing power at their disposal. Often this leads to developing ever more complex models and solutions. I have built computer models of sports surfaces for my graduate degree and occasionally as a R&D engineer and as a consultant. Most sports surfaces are very difficult to accurately model, especially across a wide range of activities. The primary reason is that the systems are made of materials with non-linear physical properties and the solutions involve non-linear physics.

For the most part, simulations look to explore the response of the surface to impacts. This type of solution is in itself a non-linear solution.

- Virtually every component of a sports surface is non-linear in its response. They tend not to have linear force strain curves under loading meaning that for an accurate solutions key traits to this non-linear response must be included.
- Virtually every component of a sports surface has visco-elastic characteristic to its properties. This means that properties change as the speed at which a force is applied to the sample is changed. Accurate simulations require the physical properties of the materials to be known within the frequency response that the model is trying to simulate and solve.

Given today's technology virtually any engineer can create pretty picture pictures from a simulation of virtually any event. I believe that too often we trust those pictures without understanding the basic physics behind the model. I believe that sometimes a very simple approach to the problem can lead to insights. I once presented such a model at an interview for a teaching position at a University. One of the engineering professors said, "That was almost like a physics class." That comment and a few years of time finally spurred the development of this publication.

OVERVIEW OF THE PHYSICS OF A FOOTSTRIKE AND THEIR RELATION TO THIS PROPERTY

Before we explore the physics of the Force Reduction properties of a surface I need to provide some plausible connection to this 'cold mechanical' test to the actual forces generated by an athlete and to provide some rational why this property may be important to the health and safety of the athlete.

The first item to cover involves a very basic review of the test equipment used to measure force reduction. The second item to cover is a very basic review of the biomechanics of running. Within this discussion we'll learn the significance of controlling impact forces and why that might benefit the athlete. This discussion will also provide you with a general background of how the standardized tests used to measure force reductions may relate to real world forces generated during sporting and athletic activity.

OVERVIEW OF TEST EQUIPMENT AND METHODS

I have provided a photo of the 'Artificial Athlete' used to perform Force Reduction on Indoor Surfaces. DIN 18032-2 coined the phrase 'Artificial Athlete', and it is now commonly found in most standards. Force Reduction is conducted using the 'Artificial Athlete Berlin, hereafter referred to as 'AAB.'

The AAB consists of a tripod that allows the unit to distribute the weight of the suspended missile well away from the impact point. The missile has a mass of 20.0 kg +/- 0.1 kg. A test foot contains a spring that helps to better mimic the impact duration associated with early foot-floor impacts and also allows the test to be non-destructive on virtually all sports surfaces (wood, synthetic, turf, indoor and outdoor). This spring has a stiffness of 2,000 kN/m +/- 60 kN/mm. The spring stiffness is approximately 13,880 lbs/in. Directly beneath the spring is a loadcell (force transducer) that allows the system to record the forces generated during impact.

Figure 1: Artificial Athlete Berlin

All test systems have some sort of signal conditioning, and an analog to digital conversion allowing the data to be sampled and then manipulated within the software on the computer. That is the purpose of the white box in the above photo.

Figure 2: Close up of Force Reduction Test Foot

The AAB is setup to impact a rigid surface (such a s concrete). These impact forces represent the baseline used to calculate the force reduction of the system. The system records the maximum force during the impact on the rigid surface (F_{rigid}). The AAB is then used to record the maximum impact force generated on the sport surface (F_{surf}). These two values are used to calculate the Force Reduction of the surface and it is expressed as a percent.

Equation 1

$$FR(\%) = \left(1 - \frac{F_{Rigid}}{F_{Surf}}\right) * 100\%$$

Using the rigid surface as the baseline, the reported force reduction level indicates by what percentage of the sport surface was able to reduce the impact force. If a surface has a force reduction of 10% then it generated a maximum force 10% less than the one generated on the rigid surface. Likewise, if a surface has a force reduction of 50% then it generated a maximum force 50% less than the rigid surface.

SELECTING SPRING AND MASS TO REPRESENT FOOT STRIKE

Tradition has it that the early developers were guided by what was commonly accepted as a typical GRF (Ground Reaction Force) of a foot during running. Figure 3[1] is an example of such a ground reaction force.

The developers focused on the early peak in the curve labeled 'Impact Peak' this is also commonly referred to as the passive peak. It takes about 50 milliseconds [2] for the nervous system to transmit information from the foot to the brain and then for the brain to send information about how to adapt to that input back to the muscles in the leg. Therefore, the loading rate should produce a peak force at or about 0.050 seconds from impact. This represents ¼ of the wavelength of the resulting spring-mass system, and corresponds to a frequency of 5 Hz

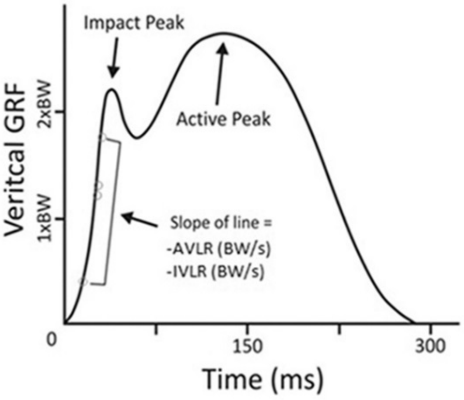

Figure 3: Typical Ground Reaction Force During Running[2]

Working with the assumption that we can view the mass as attached to the spring during the impact the natural frequency of the system can be found by the following equation:

Equation 2

$$\omega = \sqrt{\frac{k}{m}}$$

Where

ω = the natural frequency of the spring-mass system in rad/sec

k = the spring constant (2,000,000 N/m)

m = the missile mass (20 kg)

The frequency of the system is given by the following:

Equation 3

$$f = \frac{\omega}{2\pi}$$

Where

F = frequency (Hz)

The solution is that the system has a natural frequency of 50 Hz, this corresponds to a system that generates the peak loading at about 0.005 seconds after impact. This is roughly 10 times faster than the time (0.50 sec) that was considered to correspond to the passive peak. However, this is the response frequency on an infinitely rigid surface. If we consider a theoretical surface that produces approximately 50% force reduction that corresponds to a natural frequency of approximately 24 Hz.

The first section looked at the kinetic energy in the mass at the time of impact. The next component that should be examined is the selection of the spring and mass used to represent the foot strike. At the time that this method was developed those involved arrived at a missile mass of 20 kg. Their selection was certainly based in part on the biomechanics of a foot strike but it would also have taken into consideration that the AAB needed to be mobile. Too large of a weight would be cumbersome to move and lift. Their reasons for selecting this mass may never be known for certain, but for the purpose of this section we are going to simply explore how the spring was selected to complement this mass.

One of the drawbacks to this test is that tests conducted on the rigid surface are conducted at a different frequency than those conducted on compliant sports surface. Further, tests conducted on marginally compliant surfaces (10% force reduction or less) are also conducted at slightly different frequencies than those of compliant surfaces (44 Hz vs 25 Hz). Truthfully this may or may not be significant as I have not yet found a study showing ground reaction forces as a function of the mechanical stiffness of the surface. It is possible that the results produced by human participants produces similarly different loading rates.

SIMPLIFIED PHYSICS

IMPACT VELOCITY

While the impact velocity is not measured using the AAB it is of some interest, and can easily be determined. Some key assumptions are needed to simplify the solution:

- The release is clean and instantaneous, thus creating a point in time where the acceleration of the missile changes from zero to -1 g or 9.81 m/s^2 downward.
- There is no friction between the mass and guide rods during the event.

The potential energy of the missile prior to release (E_{mass}) must equal the kinetic energy of the missile at the initiation of contact (KE_{mass}). The potential energy of the missile is given by

Equation 4

$$E_{mass} = m * g * H = 10.791$$

where

m = the mass of the missile

g = acceleration due to gravity (9.81 m/s^2)

H = the release height, 0.055 m

The kinetic energy of the missile at the initiation of impact is given by

Equation 5

$$KE_{mass} = \frac{1}{2} * m * v^2 = 10 * v^2$$

where

v = the velocity of the mass in m/s

By setting the two equations equal to each other a solution for the velocity of the missile at the onset of the impact can be determined

Equation 6

$$10.791 = 10 * v^2$$

Velocity at the time of impact is 1.039 m/s.

RIDIG SURFACE IMPACT

During Force Reduction testing the AAB is set so that the missile falls 55 mm. This information along with the conservation of energy will allow us to calculate the theoretical maximum force generated on the rigid surface. Using the conservation of energy, the potential energy in the drop mass (E_{mass}) at the release must equal the energy in the spring (E_{spring}) at the time of maximum impact force. To create an even simpler system, the following assumptions were made:

1 – The spring has zero mass – this has a bearing because some of the spring is compressed therefore the actual mass of the spring would also contribute to the deflection of the spring.

2 – The spring is an ideal spring, and is completely linear in its response.

3 – The rigid surface is modeled as an infinitely large ideal mass. This assumption combined with assuming the mass of the spring is zero means that there is no transfer of momentum.

4 – All of the materials are ideal. This means that they have infinite hardness, no linear or plastic deformation occurs and there is no internal material damping.

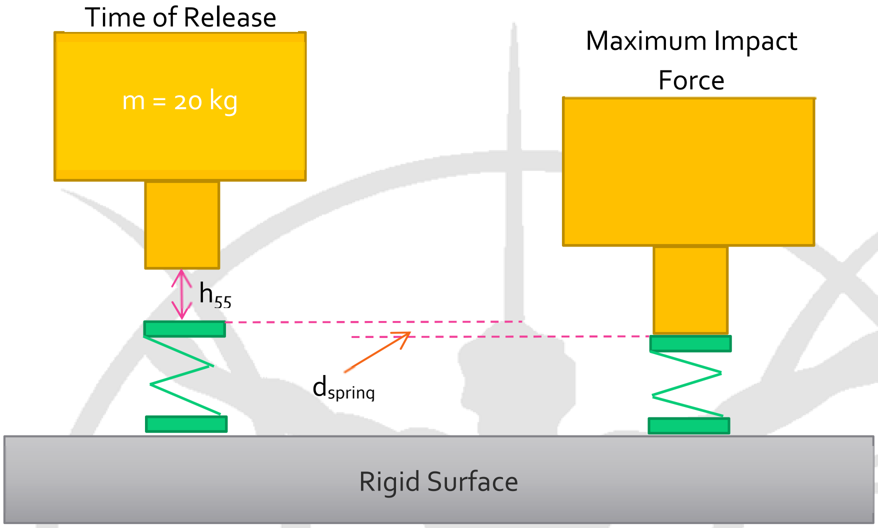

Figure 4: Simple Schematic of AAB Test System

The total vertical distance traveled by the spring is given by the following

Equation 7

$$H = h_{55} + d_{spring}$$

Where

H = the total downward vertical distance travel by the mass between its release and generation of the maximum impact force. Give the simplified properties of this model, the maximum impact force corresponds to the maximum downward deflection. Both occur when the downward velocity of the mass is equal to 0.0 m/sec.

h55 = the freefall distance specified within all force reduction standards which is 55 mm or 0.055 m.

d_{spring} =compression of the spring during the masses impact

The potential energy of the mass is given by the following:

Equation 8

$$E_{mass} = m * g * H = 20 * 9.81 * \left(0.055 + d_{spring}\right) = 196.2 * (0.055 + d_{spring})$$

Where

m = the mass of the missile

g = acceleration due to gravity (9.81 m/s^2)

H = the release height, 0.055 m, plus the deflection in the spring (d_{spring}) where both are in meters

While the energy in the spring is given by the following

Equation 9

$$E_{spring} = \frac{1}{2}k * \left(d_{spring}\right)^2 = \frac{1}{2}2E6 * \left(d_{spring}\right)^2 = 1E6 * \left(d_{spring}\right)^2$$

Where

k = the spring constant (2,000 kN/m)

Setting the two equations as equal to each other yields the following

Equation 10

$$196.2\left(0.055 + d_{spring}\right) = 1E6 * \ \left(d_{spring}\right)^2$$

Which then yields the following quadratic equation:

Equation 11

$$1E6\ (d_{spring})^2 - 196.2\left(d_{spring}\right) - 10.791 = 0$$

Equation 12

$$\left(d_{spring} - 0.003384\right) * \left(d_{spring} + 0.003188\right) = 0$$

We see that the resulting quadratic equation had two real solutions:

d_{spring} = 0.003384 m

and

d_{spring} =-0.003188 m.

One solution is negative (-0.003188m) which clearly does not fit our impact model because the overall potential energy height must be greater than 0.055 m. The negative solution actually reduces the potential energy of the mass prior to release by making the total fall height equal to 0.0518 m. This solution is disregarded. The positive solutions (0.00384 m)

The theoretical maximum force generated on the sport surface is

Equation 13

$$F = k * d_{spring} = 2E6 * 0.003384 = 6768\ N$$

The theoretical maximum acceleration experienced by the mass is

Equation 14

$$a = \frac{F}{m * g} = \frac{6768}{20 * 9.81} = 34.5$$

Where

a = the acceleration of the mass in g's

F = the maximum force exerted by the mass

m = 20 kg

g = the acceleration of gravity (9.81 m/s^2)

Note: The assumptions made in this solution also provide the theoretical maximum impact force for the mass if the new Acceleration based Artificial Athlete, or AAA, as specified by FIFA is used. The AAA method would also yield a maximum acceleration of 34.5 g's, or 34.5 times the acceleration of gravity, and a gage block is used to ensure that the AAA generates an impact velocity close to the theoretical 1.039 m/s.

SPORT SURFACE IMPACT

The next system to consider is an impact on the sports surface. This adds some complexity to the previous model. For the time being the sport surface will be modeled as a massless ideal spring. For now, this will not consider damping properties of the system or momentum transfer into the system as it moves. This system is ideal in that 100% of the energy input into the spring and floor by the missile will be returned to the mass. Later on this document will present more complex models of some of the common sports surfaces and those models will include damping and momentum. No attempt will be made to solve those models.

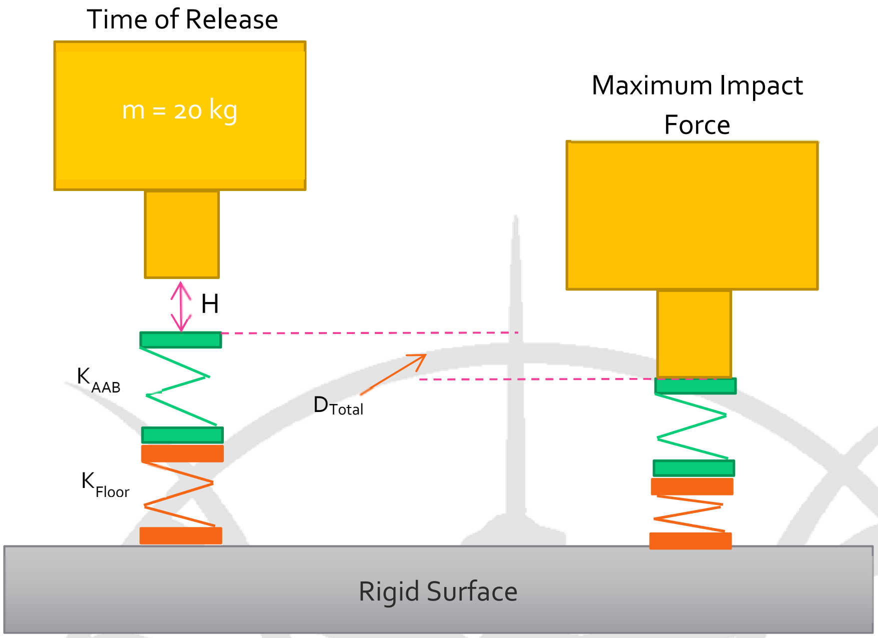

Figure 5: Simple Schematic of Combined AAB and Sports Surface Systems

The first step is to unify the two springs and determine an effective spring rate for the combined system. The following equations provide this solution.

Equation 15

$$\frac{1}{k_{eff}} = \frac{1}{k_{spring}} + \frac{1}{k_{surf}}$$

Where

k_{eff} = the effective spring rate (N/m)

k_{AAB} = the spring rate of the AAB spring (2,000 kN/m)

k_{surf} = the spring rate of the support surface

The equation can also be represented as follows

Equation 16

$$k_{eff} = \frac{k_{AAB} * k_{surf}}{k_{AAB} + k_{surf}}$$

We will be use this equation to solve for the total deflection of the effective spring. The total deformation of the combined spring then allows the force generated during the impact to be determined by the following relationship:

Equation 17

$$F_{impact} = k_{eff} * D_{Total}$$

Where

F_{impact} = the impact load applied to the system

D_{Total} = the total deflection of the system springs in meters

Because the springs are in series each one carries the same load. This means that the following equations is valid:

Equation 18

$$F_{Impact} = F_{AAB} = F_{Surf}$$

Where

F_{AAB} = the force applied to the spring in the artificial athlete

F_{surf} = the force applied to the sport surface

The force in each spring allows for the deformation of each spring component to be computed. The following equations provide the relationship between the force applied to each spring and the deflection of each spring

Equation 19

$$D_{AAB} = \frac{F_{Impact}}{K_{AAB}} = \frac{F_{Impact}}{2E6}$$

Where

F_{impact} = the impact force generated by the missile in Newtons

D_{AAB} = the deflection of the spring in the AAB in Newtons

And,

Equation 20

$$D_{Surf} = \frac{F_{Impact}}{K_{Surf}}$$

Where

D_{Surf} = the deflection of the sport surface in Newtons

The deflections of the AAB spring and of the simplified surface are related to this total deflection of by the following relationship.

Equation 21

$$D_{Total} = D_{AAB} + D_{surf}$$

Where

D_{Total} = the total deflection of the system springs in meters

D_{AAB} = the deflection of the AAB spring only in meters

D_{surf} = the deflection of the sport surface only in meters

Now that we've defined the effective spring rate, the total deformation, and the spring rates and deformations in both the AAB spring and the sport surface we can start to create a set of equations that will enable us to examine the relationship of the stiffness or spring rate of the sport surface to the impact force generated by the missile. This also yields the relationship of the spring rate of the sports surface to the force reduction levels produced by the surface.

Now that key relationships have been defined it is time to create a solution for this theoretical model. The solution will use the same relationships used to solve for the maximum theoretical impact force on the rigid surface.

The potential energy of the mass is given by the following:

Equation 22

$$E_{mass} = m * g * H = 20 * 9.81 * (0.055 + d_{Total}) = 196.2 * (0.055 + d_{Total})$$

Where

m = the mass of the missile

g = acceleration due to gravity (9.81 m/s^2)

H = the release height, 0.055 m, plus the deflection in the combined spring system (d_{Total}) where both are in meters

While the energy in the spring is given by the following

Equation 23

$$E_{spring} = \frac{1}{2} k_{eff} * (d_{Total})^2 = \frac{1}{2} * \frac{k_{AAB} * k_{surf}}{k_{AAB} + k_{surf}} * (d_{Total})^2 = \frac{2E6 * k_{surf}}{2(2E6 + k_{surf})} * (d_{Total})^2$$

Where

K_{eff} = the spring constant for the combined system. The relationship between this effective stiffness and the stiffness of the AAB spring and the stiffness of the sports surface have been previously present in this publication.

Setting the two equations as equal to each other yields the following

Equation 24

$$196.2(0.055 + d_{Total}) = \frac{1E6 * k_{surf}}{(2E6 + k_{surf})} * (d_{Total})^2$$

Which then yields the following quadratic equation:

Equation 25

$$(1E6 * k_{eff}) * d_{Total}{}^2 - 196.2(2E6 + k_{eff}) * d_{total} - 10.791 * (2E6 + k_{eff}) = 0$$

Unlike the first solution this model still has two variables. There is not one unique answer to this solution every effective spring rate has its own associated total spring deflection for the combined system. So while we have not generated a solution we have generated a relationship between the effective spring rate of the system and total deflection of the combined system. Using other equations, we can also define the impact force, deflection of the sport surface, and force reduction of the sport surface as a function of the effective spring rate. This has created a set of functions that allow the relationship between the spring rate of the surface and the impact forces to be explored.

The next step will walk through a single example solution:

- Assume a sports surface stiffness of k_{surf} 654,836 N/m.
- Plug this into Equation 15 and calculate the effective spring rate k_{eff}: 493,316 N/m
- Use this solution in Equation 25 and solve for total system deflection, use the positive solution from the resulting quadratic equation: d_{Total} 0.00702 m
- Calculate the force on the system using the effective spring rate (493,316 N/m) and the total deformation (0.00702 m) and Equation 20 to solve for the F_{impact}: 3,465 N
- Use Equation 20 and let F_{imapct} = 3,465 N then solve for the d_{surf} = 0.00529 m
- Use Equation 1 and left $F_{surface}$ = 3,465 N and F_{rigid} = 6,768 N to compute the force reduction (FR) of 48.5%

RESULTS

A spread sheet has been generated that performs all of these solutions quickly. Contact ASET Services (info@asetservices.com) to request a copy. The following graphs were developed within that spreadsheet.

This first graph shows the combined deflection of both the AAB and sports surface as a function of the Sport Surface Stiffness. I've included a first version in a linear scale just to show that on a linear scale very little information is present. The deflection points that lie along the horizontal X axis show that deflections change very little in this range as stiffness is changed. The deflections that lie along the vertical Y axis show that deflection change quite a rapidly as stiffness is changed.

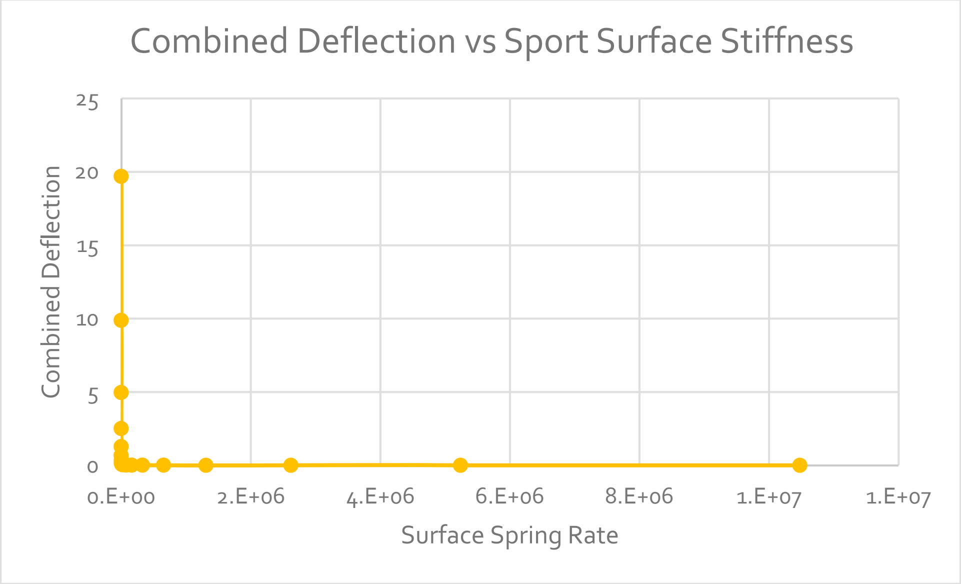

Figure 6 Combined Deflection Vs Sports Surface Stiffness (Linear Scale)

Here is the same graph but with a logarithmic X Axis. This shows that the relationship between the two variables is extremely non-linear.

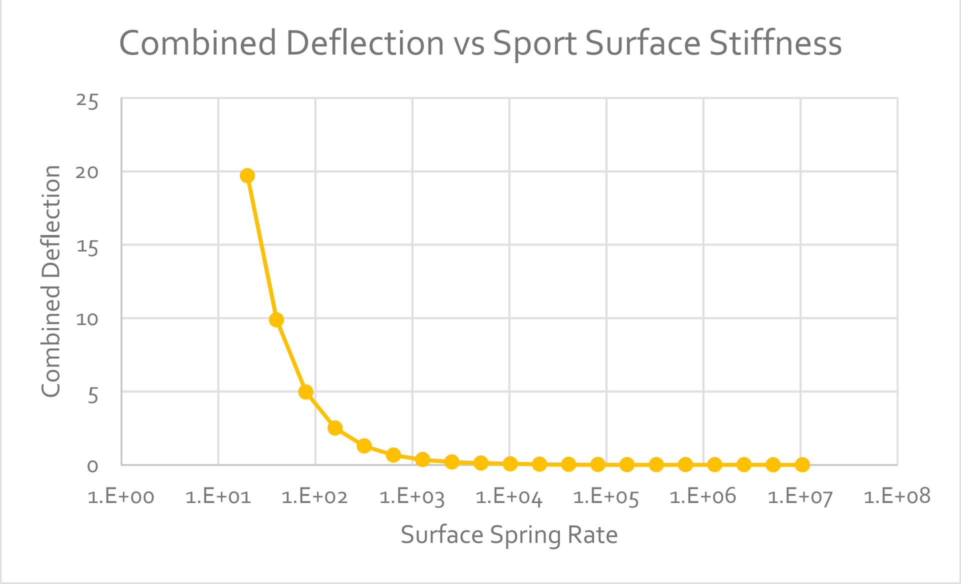

Figure 7: Combined Deflection Vs Sports Surface Stiffness (Log Scale)

Combined deflections are really not of much importance. The following graph shows the deflection of the sports surface versus the sport surface stiffness. Once again that X axis is a logarithmic scale.

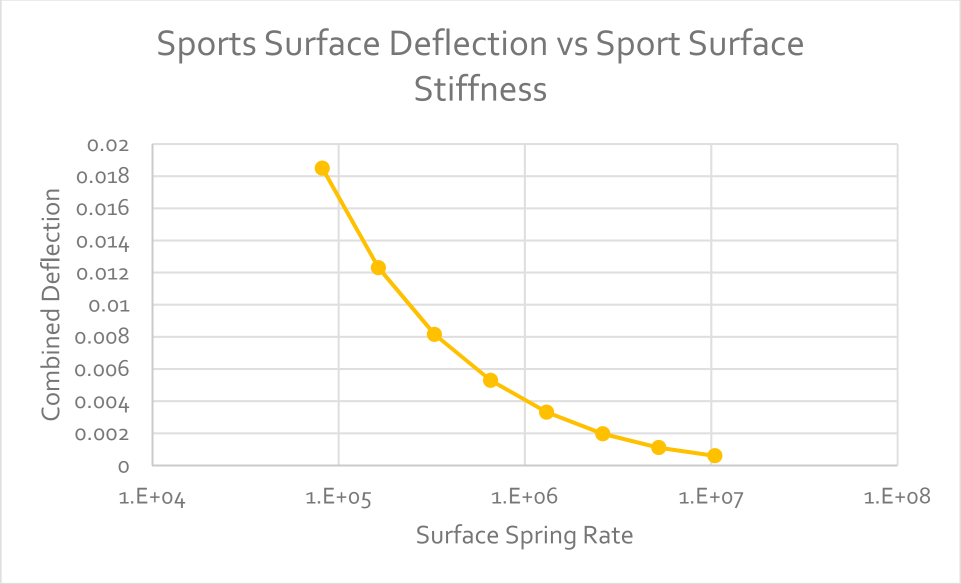

Figure 8: Deflection of Sports Surface Only vs Sports Surface Stiffness (Log Scale)

The data in the previous graph represents the force reduction of surfaces ranging from roughly 78% to 7%. The force reduction level versus the sports surface is shown in the following graph.

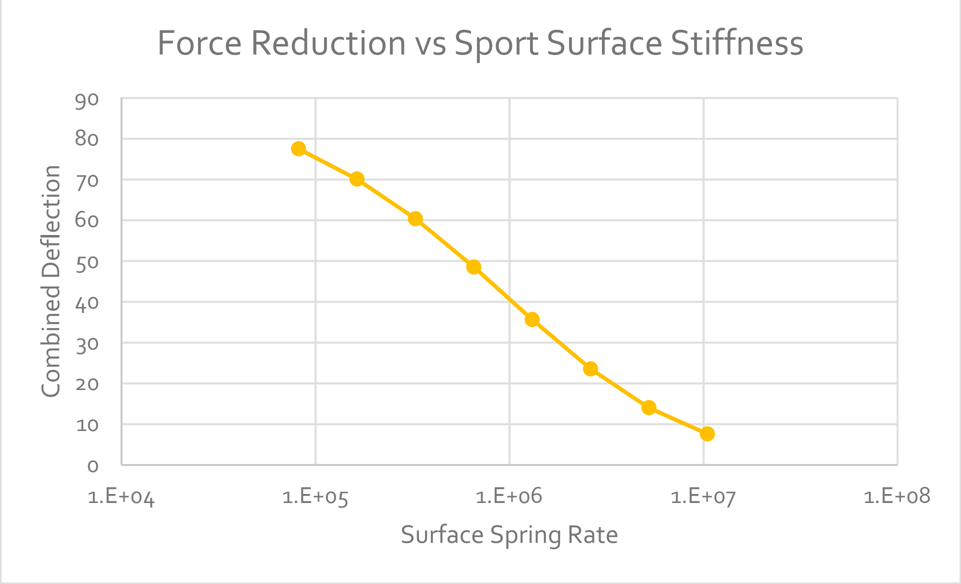

Figure 9: Force Reduction vs Surface Stiffness (Log Scale)

Figure 9 seems to show a linear relationship but the Spring Rate of the Surface is presented on a Logarithmic Scale. When the same data is presented in Figure 10, it shows the non-linear relationship between force reduction and Surface Stiffness or Spring Rate.

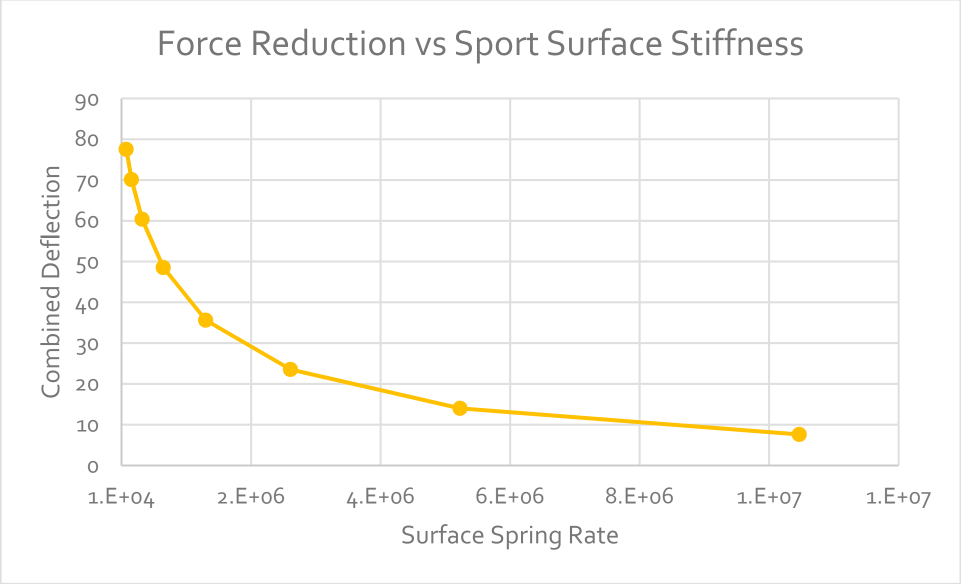

Figure 10: Force Reduction vs Surface Spring Rate (Linear Scale)

The data in Figure 10 highlights the non-linear relationship between the stiffness of the surface and the force reduction measured by a Berlin Artificial Athlete or even a new AAA artificial athlete. This theoretical model shows that a similar difference in force reduction (say 5%) is effected quite differently by changes in the stiffness of the sport surface depending on which portion of the line in Figure 10 the surface is. The following table contains two examples

Force Reduction Change	Surface Stiffness Change	Percent Change in Surface Stiffness
5% (increasing from 5% to 10%)	2900 kN/m	28%
5% (Increasing from 55% to 60%)	110 kN/m	28%

Both regions of the curve (5-10%, & 50-55%) require that the surface stiffness is reduced by approximately 28% in order to increase force reduction by 5%. However, relatively hard surfaces (in the 5% to 10% section of the curve) require that the surface stiffness be reduced by 2,900 kN/m and relatively soft surfaces (in the 55% to 60% section of the curve) require that the surface stiffness only needs to reduce by 110 kN/m. Using this example, the stiffness change needed for a hard surface must be 26 times or 2,600% larger than the change needed for the softer surface.

This simplified approach shows that a 5% difference in force reduction represents significant changes to the stiffness of the surface (28%), and that is useful. However, remember this is a very simplified model and several international studies have shown that the equipment really has about a +/-3% to +/-4% confidence window or error. This means that you cannot use this simple model to justify a specification that throw out products with very similar results simply because this theoretical solution shows that the surface stiffness may be very different.

One can consider historical evidence and informal case studies to determine if this model can be further justified. Several years ago I visited a University and tested two of their floors. I spoke with the coaches and they said all of their players preferred the game court to the practice court. Testing revealed that the game court had a force reduction level of 12% and the practice court had a force reduction level of 11%. It also revealed that the hardest point on the game court produced a force reduction level of 8% while the hardest point on the practice court produced a force reduction of only 4%. The 1% difference between the two courts falls within the repeatability associated with the equipment so there is not a strong case that the athletes felt the 1% difference. However, it is likely that the differences of 4% between the hardest points represents actual differences in force reduction. Such a case study suggests that athletes can perceive a 4% difference and make it possible that they can even perceive a 1% differences if the effects are cumulative over a 1-2 hour practice.

SUMMARY:

Using a very simplified model we've been able to explore the sensitivity of the measured force reduction to the stiffness of the surface. We have learned that the response is far from linear. We've also learned that the surface stiffness must change significantly more in absolute terms (2,600 % more) on a hard surface to achieve a 5% increase in force reduction than on a more complaint system. We've learned that no matter where a system lies on the curve a 5% change in force reduction requires a relatively significant change (28%) in the stiffness of the surface. I'll say that as a researcher and designer this parallels my experience small changes in the stiffness of a system rarely result in significant changes in the force reduction of that system.

In order to achieve this high level view of the force reduction tests and measurements we had to make serious assumptions. The largest one being that we assumed linear behavior throughout the system, when virtually every part of a sport surface system is non-linear or viscoelastic. All synthetic components would have significant damping within them and that has been completely ignored. The flex between and within key layers has been completely ignored. We've further ignored energy lost to sound and vibrations within the test surface. We've ignored energy lost by placing portions of the system in motion and their kinetic energy loss. We've ignored the friction of the missile as it drops down the guide rods. So, while these results provide some insight into the test but they do not provide accurate relationships or predictions.

Another key assumption is that the linear property of the sport surface continues through the entire theoretical compression. Numerous systems are too thin for the surface to fully absorb the impact energy. This means that the stiffness of the system rapidly increases toward the end of the impact. Systems with this property will produce very high impact forces.

Every sport surface can be boiled down to this basic model. That means that it provides a general view of rubber, hardwood, vinyl, crumb rubber / urethane, poured urethane and synthetic turf. That also means that it is a very general model and that it does not predict any of them particularly accurately.

While this simplified view is limited in application we were able to quickly explore how force reduction might be effected by the properties of the surface. While noise, friction and damping would create a much different model, I believe this model serves as a starting point and shows that significant changes will be needed in the properties of the sports surface to bring about measurable and meaningful changes in the force reduction of the sports surface.

This model can be explored in more detail to glean a few more bits of information but that goes far beyond what I'd consider a basic view of this simplified model. In fact, I realize that there are probably not too many out there that view this as a simplified model, but every part of this simplified model can be solved by hand using a calculator.

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