Artificial Athlete Berlin updated 12.2.2000
Comments on Function and Use

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These comments were prepared as an addition to Mark Harrison's extensive study on *Factors Affecting the Results of the 'Berlin Artificial Athlete' Shock Absorption Test (9/99)*. The following comments are issued in cooperation with Bernd Härting (IST Leipzig).

1. Scope of Test

The test was developed by FMPA-Baden-Württemberg (Otto-Graf-Institut) in Germany during 1976 as a piece of sponsored research initiated by the Bundesinstitut für Sportwissenschaft (Federal Institute of Sports Sciences BISp) in Cologne. It was designed to test the give of sports surfaces in-situ/on-site. The test was first specified in the German standard DIN 18032-2 *"Sports Halls; Sports Surfaces; Requirements and Testing".* The test was then incorporated into DIN 18035-6 *"Sports Grounds; Synthetic Surfaces; Requirements, Testing, Maintenance"* (playing areas) and DIN 18035-7 *"Sports Grounds; Synthetic Turf Areas"*, DIN 7926 Part 1 *"Equipment for Children Playgrounds".* The following international documents include this test*: IAAF Performance Specifications for Synthetic Surfaced Athletics Tracks (Outdoor)* and the *FIH Handbook for Synthetic Hockey Pitches – Outdoor*.

There are 2 variants of the test procedure: the first filters the signal with a cut-off frequency of 120Hz (DIN 18032-2) and the second filters with 220Hz (DIN 18035-6). The reasons for the different filters are given in a later section of this paper.

The test procedure has been subjected to various changes over the time which, did not change the test, but improved the accuracy. The most important innovation was the new triple-coil milled spring. Its spring number is manufactured to an accuracy of 2'000 MN/m +/- 0.050. The other major improvement is the digital data acquisition technique (A/D converter and computer driven data acquisition and recording).

2. General Structure and Function

The structure of the test apparatus and the test procedure are described in DIN 18032-2 (current version 1986/1991).

If the AA Berlin is used on a concrete floor, it can be regarded a simple **single-mass swinger**. Based on M. Harrison’s formulas the impact approximates the equation:

$$\boxed{y = (x - M \,.\, g / k) \,.\, \sin (w \,.\, t) + M \,.\, g / k}$$

where

y = deformation of spring in m

x = maximum compression of the spring = 0.00338m

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

M = mass of drop weight = 20.0kg

k = spring constant = 2.0 MN/m

t = time in seconds

w = expresses resonance frequency = Ö k / M = 316

f_r = resonance frequency = w / (2 . p) = 50Hz

$$\boxed{v = -(0.00338 - M \,.\, g / k) \,.\, w \,.\, \cos(w \,.\, t)}$$

$$t = 0 \dashrightarrow \mathbf{v_0 = 1.04\ m/s}$$

$$F = y \,.\, k$$

$$F_{max} = x \cdot k = 6760N$$

However, in normal usage, the Artificial Athlete is a **two-mass swinger**. If the Artificial Athlete rests upon a soft sports surface (Force Reduction > 50%), the lower mass starts a vibration with a resonance frequency considerably higher than the resonance frequency of the 1-mass swinger (see figure 1). Based on experiments upon various soft sports surfaces including the ReferenceNormals, it can be shown that the frequency of the superposed oscillation is in the range of 130Hz to 230Hz. While rather independant of the softness of the 'sports surface', this is dependant on the individual mechanical test device used (information gained by measuring the time of full cycles of the superposed oscillation on the graph). The frequency of the basic test signal decreases to values below 20Hz because of the softness of the 'sport surface'. The softer the 'sports surface' the larger the amplitude of the superposed oscillation. This may result in a difference of Force Reduction of more than 10% of the absolute value (evaluation with unfiltered signal compared with the 120Hz filtered signal).

According to the latest specification of DIN 18032-2, the mass of the lower mass should be 3kg. The resonance frequency of the lower mass with the spring of the Artificial Athlete would then be 130Hz. It becomes higher the lower the mass.

The reasoning for the size of the amplitude in dependance to the softness and the damping chacteristics of the 'sport surface', is derived from the solution of the differential equations of the 2-mass swinger (performed at FMPA in the 70's; not available anymore; see also G. Pratt's study).

The superposed oscillation must be eliminated from the signal, which is the information that the test was designed to produce. This is achieved by use of a low pass filter with a cut-off frequency of 120Hz. According to DIN 18032-2, this applies to sports hall surfaces only. Other soft surfaces such as synthetic turf surfaces and playground surfaces are to be treated according to type (see DIN standards).

If the lower mass is neglected (for reasons of simplification) the effective spring number/constant/rate **k** of the combined system Artificial Athlete + sports surface is as follows

$$1 / \mathbf{k} = 1 / k_1 + 1 / k_2$$

where

k_1 spring rate of the AA
k_2 spring rate of sports surface (assumed to be a constant)

if k_2 is set to

$$k_2 = f \,.\, k_1$$

then

$$\mathbf{k} = k_1 \,.\, f / (1 + f)$$

Inserting this in

$$FR = 1 - F_{ss} / F_{concrete}$$

gives

$$FR = 1 - \mathrm{SQRT}\{ f / (1 + f) \}$$

This function is displayed in figure 2. It can be seen that the Force Reduction is 30% when the spring rate of the sports surface is equal to the AA's spring rate (f=1). The Force Reduction is about 10% when the sports surface is 5-times stiffer than the AA's spring.

3. Measuring Technique

It is assumed that digital measuring technique is standard today (analog signal acquisition and digital signal processing).

Load Cell

The load cell needed for the test is specified in DIN 18032-2. No further comment is necessary. With the low frequencies of all situations occurring on sports surfaces, it does not matter whether it is a strain gage or piezo-electric system (was critical in 1976 when this was a question of confession). However, the give of a strain gauge load cell has to be taken into account ('spring rate' may be in the range of 50'000 to 100'000 N/mm).

Amplifier / Signal Conditioner

The capacity of the signal conditioner is also specified in DIN 18032-2. It should have a linear signal transmission with a minimum of 1kHz (-3dB). With commercial equipment from qualified manufacturers this is no problem. Amplifiers normally have a built-in filter in order to eliminate noise from the signal (for instance 500Hz Butterworth 2-pole).

A/D Converter

The DIN did not anticipate that measurements would be performed with digital data acquisition systems. Today, this is regarded the standard in measuring technology. A/D converters with 12bit capability meet the needs of the test. The number of conversions per second needed is easily performed by modern ADCs.

Recording

Signals from the AA Berlin should be processed with a computer. The signal should be displayed on a screen to visually check its regularity. Then, it should be processed and evaluated to be read as Force Reduction.

Filtering

Filtering of the signal is needed for two reasons: first, the high frequent vibration or noise of the metal parts of the Artificial Athlete (undamped impact of the metal drop weight onto the metal spring) and secondly, the superposed oscillation of the lower mass of the Artificial Athlete. The first aspect is covered with any 500Hz (minimum) low pass filter. The second aspect is addressed with additional filtering of a 120Hz filter of Butterworth characteristic with 9 poles or equivalent. A 2-pole Butterworth filter does not have a sharp enough separation capability to completely eliminate the superposed/parasitic oscillation.

When using a computer, a data acquisition programme such as EASYEST, TESTPOINT or the like is needed. The TESTPOINT programme contains a filter module emulating a Butterworth filter with x poles. It can be applied to transient and continuous signals. The filtered signal exhibits a considerable time lag and a slight overswing compared with the original signal (i.e. peak force of filtered signal is slightly larger than the unfiltered ideal curve).

In the past (and still valid for EASYEST users) only FFT based filtering was available with these programmes. It was necessary then to adjust the FFT based filtering to the Butterworth filter. Since very little information on digital filtering is available, this task must be performed by practical determination of the frequency response of the filter system. It was found that the steepness of the filter function beyond the cut-off frequency is influenced by the sampling rate in relationship to the cut-off frequency. For a cut-off frequency of 120 Hz, the sampling rate must not be higher than 2000Hz with the EASYEST programme. When this rule is violated in TESTPOINT, no filtering effect occurs at all. FFT filter can be applied to transient signals only (number of points must always be a power of two). There is no time lag between the filtered and the unfiltered signal and no overswing.

It is an error to believe that the 130Hz – 230Hz oscillations are created by internal 'problems' of the Butterworth filter (i.e. self-originated by the filter modul) as stated in the DIN 18032-2 committee.

Evaluation

The evaluation of Force Reduction is easy if springs comply with the current level of accuracy available today (see above). No corrective term is then necessary as is found in the 1986/1991 version of DIN 18032-2.

4. Precision

Error Considerations

It is of major importance to know about the possible errors and their effects on the results (i.e. Force Reduction).

Reference Peak Value (1)

Mark Harrison's study deals with the factors influencing the peak force of the Artificial Athlete Berlin on concrete. If the accuracy of the drop weight and the drop height are within specification, the peak force will not vary more than +/- 15N. If the spring constant deviates by 40N/mm the peak force error is 65N.

It is important to specifiy how the peak force on concrete is to be determined. Experimental data shows that using a 120Hz FFT or Butterworth filter with 2 poles disfigures the result by a few percent. Not using any filtration leads to an incidental result since the high frequent vibration is not repeatable/consistant from impact to impact and from test device to test device. However, a sufficient repeatability is achieved by applying a min. 220Hz filter (see Mark Harrison's study).

The quality of the concrete base is less important than believed by some labs. To recognize whether a concrete base or floor is suitable, it is necessary only to examine the concrete surface after the tests. If there is any damage the surface is not suitable. Placing a steel panel/plate on the concrete surface, to harden and reinforce it, helps to eliminate the possiblity of a problem with the concrete base. If the effective mass of a concrete base in the lab is not known, the usability of the base can be determined by comparison tests with the AA on a concrete base with known mass.

Reference Peak Value (2)

What happens if the peak force value is mistaken in the formula to evaluate FR? The formula is

$$FR = 1 - F_{ss} / F_{concrete} \text{ and } FR = 1 - F_{ss} / F_{concrete}$$

where

FR = correct Force Reduction
F_{ss} = peak force on sport surface
$F_{concrete}$ = peak force on concrete
x = the error factor and
$F_{concrete}$ = the erroneous peak force on concrete and
FR = the erroneous Force Reduction

Then the error function is

$$FR = 1 - (1 - FR) . \mathbf{x}$$

With

$$F_{concrete} = \mathbf{x} \cdot F_{concrete}$$

With the same magnitude of the error factor **x** the error in FR increases dramatically the lower FR (see figure 3)

Peak Force on Sports Surface

A similar consideration can be applied to the case that F_{ss} is determined with an error.

$$FR = 1 - F_{ss} / F_{concrete}$$

$$FR = 1 - F_{ss} / F_{concrete}$$

$$F_{ss} = \mathbf{y} \cdot F_{ss}$$

$$FR = (\mathbf{y} - 1 + FR) / \mathbf{y}$$

With the same magnitude of the error factor y the error of FR increases dramatically the lower FR (see figure 4).

Spring Constant

One of the most interesting factors is the effect from deviations in the spring constant beyond the specified range. In order to understand the problem in principle, the simplified Artificial Athlete (i.e. no lower mass) is used.

The incorrect spring constant is

$$K = z \cdot K$$

With this, the formula of paragraph 4.1.4 is modified as follows (see figure 5) (formula has still to be verified):

$$FR = 1 - \mathrm{SQRT}\{ z \cdot f / (1 + f) \}$$

Improvements

Aside of calibration, it is necessary to have a method to regulate all members of the measuring chain and to have a method to control the compliant functions of the various test devices. In the past, this was often achieved by using samples of sports surfaces which were circulated between the test labs. Since real surface samples are not constant over the time another method was developed by SKZ. The surface replacement – called ReferenceNormals - consists of from 3 to 6 washer springs of specified characteristics mounted in a metal cache. The ReferenceNormals are manufactured and 'calibrated' by SKZ. To date, only one specific grade has been created: FR = about 53%. The calibration is performed by comparing a new ReferenceNormal with an Ancester-ReferenceNormal the Force Reduction of which was determined within a Round Robin in Germany. The ReferenceNormal method is included in the 1998 draft of DIN 18032-2 as a calibration method which is believed to eliminate all problems with excessive peak force values on concrete or deliberate use of filters. With the ReferenceNormal, the results of inaccurately functioning AAs are corrected by using an additive term: the difference between the nominal Force Reduction of the ReferenceNormal and the actually measured FR with the device to be calibrated determines the additive parameter:

$$FR = (1 - F_{ss} / F_{concrete}) + ?\ FR$$

The specification of the ReferenceNormal in DIN 18032-2:1998 is incomplete. In practice, however, the method is very helpful since the ReferenceNormal is an easy and reliable means of controlling the accurate operation of the test equipment. The IST has retested its ReferenceNormal 5-times since 1998. The results varied within 0.4%. The DIN must be amended with an acceptable calibration procedure for the ReferenceNormal. The ReferenceNormal can be designed with various grades of softness in order to simulate 30%, 50% and 60% Force Reduction.

5. Practical Consequences

Design of Test Apparatus

Mechanically, the most important aspect of the Artificial Athlete is the assurance that a minimum level of friction occurs in its moving parts. The friction of the drop weight against the guiding rods is minimized by using teflon-covered tubes 1mm larger in diameter than the rods. Unfortunately, this is not mentioned in DIN 18032-2.

DIN 18032-2 does not require the new triple-coil milled spring, (Rein spring named for its developer and manufacturer, the Rein Company in Urach, Germany). The DIN requires only a spring with a static spring constant of 2000MN/m +/- 0.060 and linear characteristic of up to 10kN.

This requirement may be met by springs of classic style (single-coil, bent). However, springs of this type cannot be manufactured to anywhere near the same accuracy.

Springs consisting of a package of single springs are problematic since the accuracy of the individual springs, especially their length, is low (taken from engine valves). They have to be pre-stressed in order to avoid an undefined start section of the load-deformation characteristic. Such springs need special investigation in order to be sure of getting correct results.

Measuring Technique

The measuring chain shall consist of commercially designed and manufactured elements from established manufacturers/ suppliers only. All relevant technical data must be available.

The amplifier must transmit signals up to 1kHz (3dB).

The measuring chain shall include a visual check of the signal (display on computer screen or transient oscilloscope).

Calibration

The calibration should be performed in two different ways.

First, all components of the measuring chain must be checked and adjusted/calibrated according to established rules of measuring technology. Each component must meet the requirements.

Verification of the frequency response of the filter modul needs to be conducted. The frequency response must comply with a Butterworth 9-pole filter characteristic.

To calibrate the AA, a frequency response diagram must be established using the specific measuring chain.

The peak force on concrete must comply with the range of 6.4kN to 6.7kN using a 220Hz – 500Hz filter or equivalent.

The spring needs static calibration using an appropriate calibration device (see figure 6).

Second: the measuring chain including the mechanical parts must be checked with a ReferenceNormal. However, the physically correct method must still be developed (see paper ‘Artificial Athlete Berlin: Operating the ReferenceNormal Right’).

The calibration of the ReferenceNormal can be achieved by using specific ISSS owned devices which are regularly circulated among ISSS members. The average of 4 labs (minimum) with compliant results is critical to this procedure.

An individual test device needs correction if it differs by more than 0.5% from the assigned/nominal ‘true’ value of the ReferenceNormal.

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