Running Shoes—Possible Correlations of Biomechanical and Material Tests †

Markus Eckelt * and Franziska Mally

Department of Life Science Engineering, University of Applied Sciences Technikum Wien, Vienna 1200, Austria; mally@technikum-wien.at

* Correspondence: eckelt@technikum-wien.at; Tel.: +43-1-333-4077-6240

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Abstract: Today's development of running shoes is often supported by the assessment of biomechanical tests (BIOs) as well as material tests (MATs). In order to possibly reduce the number of relevant tests, the aim of this study was to find out whether there are correlations between the selected BIO and MATs. Therefore, four different running shoes were tested. For the BIO, the ground reaction force and tibial acceleration of 19 experienced runners were measured. The evaluated parameters were first peak, time to first peak, impulse during the first 75 ms of stance, maximum vertical ground reaction force, loading rate, mean peak acceleration and median power frequency. The MATs included compression tests and an impact test with and without insoles at the forefoot as well as the heel area. The results show that carrying out MATs (especially impact tests) without insoles give the most insight into the parameters analysed with the BIO.

Keywords: running shoes; biomechanical test; material test; compression test; impact test

1. Introduction

Today, a conventionally produced running shoe consists of up to 40 different materials and individual parts or construction elements [1,2]. These parts are commonly stitched and glued together in a very specific way. However, due to the advancements in additive manufacturing methods, individually fitted running shoes have been manufactured through 3D printing using the selective laser sintering (SLS) process. For example, the midsoles of the new Adidas Futurecraft (Adidas AG, Herzogenaurach, GER) and the New Balance Zante Generate (New Balance Athletic Shoe, Inc., Boston, MA, USA) were entirely 3D printed using SLS. To manufacture such a running shoe, computer-aided engineering is needed. The shoe design was initially created using computer-aided design, followed by a finite element analysis (FEA). The results of the FEA indicate whether the design could withstand the occurring mechanical stress while in use. If the mechanical results are within a feasible range, a first prototype can be produced. However, the mechanical properties of parts produced via SLS are influenced by the fabrication parameters and the material used [3,4]. Furthermore, the actual mechanical behaviour of the manufactured parts may differ from the predicted results of the FEA [5,6]. Therefore, material tests (MATs) and biomechanical tests (BIOs) have to be carried out to verify and validate the 3D-printed prototypes. These test results can further be used to evaluate and, if necessary, further optimize the design. On the one hand, this new possibility of an SLS manufacturing process could eventually save a lot of time. On the other hand, to carry out a great number of verification and validation tests (MATs and BIOs) will take a lot of time in return.

Therefore, the aim of this study was to find out whether there are correlations between the analysed parameters of this study's BIO and MATs, so that in the future, it might not be necessary to

carry out all tests, as due to the notion that one tested parameter conclusion can be drawn to another usually tested parameter. Furthermore, to measure the influence of the insole on the results of the MATs, all MATs were carried out with and without the insole of the running shoe. It was hypothesized that

H1₀. *there will be no correlations between the variables of the BIO and the MAT carried out with the insole of the running shoe.*

H2₀. *there will be correlations between the variables of the BIO and the MATs carried out without the insole of the running shoe.*

2. Materials and Methods

2.1. Running Shoes

Four different types of running shoes were tested:

- Asics GEL-NIMBUS 18, which is stated as "one of ASICS' most recognised high performance footwear". This running shoe uses the "rearfoot and forefoot gel® technology for its cushioning systems", which should attenuate shock during impact and the toe-off phase [7];
- Brooks GLYCERIN 14, which due to its "super DNA midsole" and its pressure zones on the outsole is a running shoe with a "super-soft cushioning" [8];
- Cloudsurfer, which uses an open-cell technology where every single element is called a cloud. The Cloudsurfer has 13 clouds that provide a "soft landing" and a "dynamic kick" for the runner [9];
- Cloudflyer, which uses an open-cell technology and consists of 12 clouds that provide cushioning as well as stability [10].

2.2. Participants

Nineteen experienced runners (7 m., 12 f.), with an average age of 28 ± 4.6 years, a height of 170 ± 8 cm and a body mass of 64 ± 9.5 kg, voluntarily participated in the BIO. The inclusion criteria for participations were as follows: (1) participants have completed a minimum running distance of 16 km/week; (2) the minimum preferred running speed of 3 m/s; (3) run with heel landing (heel-toe running); (4) wear running shoe size between 38 and 43 EUR; and (5) had no injuries to the lower extremities within the past year.

2.3. Experimental Protocol—BIO

Participants were asked to wear a pair of the selected running shoes at a time and to run on a measurement track. The whole measurement track had a length of 30 m, where one force plate (AMTI OR6-7, Advanced Mechanical Technology, Inc., Watertown, NY, USA) was placed midway on the track. A valid trial was defined by reaching a running speed of 3 ± 0.2 m/s, which was determined by two light barriers that were placed in the measurement area (one just before and the second one right after the force plate). Every participant had to accomplish ten valid runs with each pair of running shoes. Data of the force plate were sampled with a frequency of 1000 Hz and were amplified with the MiniAmp MSA-6 (Advanced Mechanical Technology, Inc.; amplification factor: 2000). The amplified data were digitised by the use of a Vicon MX-Control and were stored with the software Peak Motus 9.0.2 (both Vicon Motion Systems, Inc., Oxford, UK).

A low-mass uniaxial acceleration sensor (ADXL321, Analog Devices Inc., Norwood, MA, USA) was attached to the distal anteromedial aspect of the participants' tibia by using medical double-sided adhesive tape [11]. This position was chosen to reduce the effects of soft tissue vibration. The axis of the sensor was aligned with the longitudinal axis of the participants' lower leg while standing and wearing the running shoes. Data were sampled with a frequency of 1000 Hz and

stored on a datalogger (logomatic V2, SparkFun Electronics, Niwot, CO, USA), which the participants carried in a belt.

The data of the force plate was filtered via a low pass Butterworth filter (second order) with a cut off frequency of 140 Hz. The first peak (F_1), time to first peak (t_{F_1}), impulse during the first 75 ms of stance (I_{75}), maximum vertical ground reaction force (F_{VGRF}) and vertical average loading rate [12] (LR) were analysed [11]. All force magnitudes were normalised to the body weight (BW) of each participant.

Data of the acceleration sensor were filtered with a low pass Butterworth filter (second order) with a cut off frequency of 60 Hz [13]. After filtering, the first tibia head acceleration peak was determined for all steps and the mean peak acceleration (MPA) was calculated for each type of shoe. The median power frequency (MPF), representing the median frequency of the fast Fourier transformation, was determined out of the unfiltered data of the acceleration sensor during the stance phase.

2.4. Experimental Protocol—MAT

The running shoe soles (size 42 EUR) were prepared according to the ASTM F1976 [14]. The centre of the measurement area for the heel (HA) was marked at 12% of the internal length of the top surface from the heel and equidistant from the medial and lateral edges. The centre of the measurement area for the forefoot (FA) was marked at 75% of the internal length of the top surface from the heel and equidistant from the medial and lateral edges. All tests were carried out on test benches with an indenter, as described in the ASTM F1976 (cylindrical with a circular face of 45 ± 0.1 mm and an edge radius of 1.0 ± 0.2 mm). Every type of running shoe was tested ten times at the HA and FA with and without the insole.

For the compression tests with a low loading condition, a force of 400 N was applied by the use of a captive hybrid linear actuator (57H4R-05-825ENG, Haydon Kerk Motion Solutions, Inc., Waterbury, CT, USA) with a linear travel per step screw of 0.0079 mm. The signal of the force transducer (S2M/1000N, Hottinger Baldwin Messtechnik GmbH, Darmstadt, Germany) was captured using the data acquisition card NI USB-6008 (National Instruments Corporation, Austin, TX, USA) at a sampling frequency of 500 Hz in a Labview routine (National Instruments Corporation, Austin, TX, USA).

For the compression tests with a high loading condition, a force of 1650 N was applied by the use of a screw jack system (M8CB4, ZIMM Maschinenelemente GmbH + Co KG, Lustenau, Austria). The applied force was captured via a load cell with a measuring range of 5000 N (RSCA C1, Hottinger Baldwin Messtechnik GmbH). A laser distance sensor was used to capture the displacement (LDS85/705, ELTROTEC Sensor GmbH, Uhingen, Germany). The data of both sensors were digitised with the data acquisition card NI USB-6211 (National Instruments Corporation) at a sampling frequency of 500 Hz and stored using a Labview application.

Impact tests were carried out following the ASTM F1976. The drop height of the gravity-driven missile assembly was set so an energy of 5J was applied to the test specimen. The applied force was captured with the RSCA C1 (measuring range: 5000 N, Hottinger Baldwin Messtechnik GmbH). Displacement was measured by the use of a rectilinear displacement transducer (PME12, GEFRAN S.p.A., Provaglio d'Iseo, Italy) with an electrical stroke of 300 mm. The data of both sensors were digitised with the data acquisition card NI USB-6211 (National Instruments Corporation) at a sampling frequency of 500 Hz and stored with a Labview application.

Data of the force transducer and the load cell were filtered with a forward–reverse moving average filter (window size: 25). The maximum displacement (Disp) and the energy that represents the area of the force as a function of the displacement curve were calculated.

2.5. Statistical Analysis

With all datasets, a Kolmogorov–Smirnov test was performed to ensure a normal distribution using Microsoft Excel 2010 (Microsoft Corp., Redmond, WA, USA). For the investigation of the relationship between the mean values of the parameters of the BIO and MATs, the Spearman

rank-order correlation coefficient was calculated using the GNU Octave (version 4.0.3) software. Correlation coefficients above 0.95 were defined as a high (positive linear) correlation, whereas a correlation coefficient below −0.95 was defined as a high negative linear correlation. Significance was calculated with the Mann–Whitney U-test, where the level of significance was defined as $p < 0.05$.

3. Results

Table 1 shows the calculated mean values as well as the standard deviations for the BIO with the four types of running shoes.

Table 1. Results (mean value ± standard deviation) for the biomechanical test (BIO) with the four types of running shoes.

Parameter [Unit]	Asics	Brooks	Cloudflyer	Cloudsurfer
MPA [g]	7.4 ± 1.91	8.54 ± 1.66	7.93 ± 1.78	9.24 ± 1.8
MPF [Hz]	6.86 ± 2.16	7.67 ± 2.63	7.79 ± 3.12	8.41 ± 2.41
F_1 [BW]	1.71 ± 0.29	1.76 ± 0.3	1.74 ± 0.22	1.73 ± 0.3
t_{F1} [ms]	45.7 ± 8.7	38.3 ± 5.1	34.1 ± 4.8	34.1 ± 4.7
I_{75} [N*ms]	113.7 ± 22.9	126.6 ± 24.5	126.4 ± 19.7	131 ± 22.6
F_{VGRF} [BW]	2.53 ± 0.23	2.53 ± 0.25	2.51 ± 0.22	2.51 ± 0.22
LR [BW/s]	37.40 ± 0.63	45.97 ± 7.83	50.99 ± 6.45	50.81 ± 8.9

Table 2 shows the measured Disp and the calculated energy for all MATs with the four running shoes at the FA and HA with and without the insole.

Table 2. Measured Disp and calculated energy for all material tests (MATs) with the four running shoes.

Parameter [Unit]	FA				HA			
	Asics	Brooks	Cloudflyer	Cloudsurfer	Asics	Brooks	Cloudflyer	Cloudsurfer
Compression test - low loading condition (force: 400 N) with insoles								
Disp [mm]	8.9 ± 0.1	8.7 ± 0.2	6.7 ± 0.2	7.7 ± 0.2	9.4 ± 0.2	9.4 ± 0.2	8.7 ± 0.2	9.9 ± 0.4
Energy [N*mm]	155.1 ± 9.8	164.9 ± 2.6	142.4 ± 2.7	129.3 ± 1.4	160.5 ± 1.3	162.8 ± 1.1	163.8 ± 2.4	159.1 ± 1.9
Compression test - low loading condition (force: 400 N) without insoles								
Disp [mm]	6.9 ± 0.2	6.4 ± 0.3	5.3 ± 0.2	6.2 ± 0.2	7.8 ± 0.3	7.3 ± 0.6	5.5 ± 0.3	6.3 ± 0.2
Energy [N*mm]	154.3 ± 8.8	171.7 ± 3.3	135.3 ± 2.6	142.5 ± 5.2	165.7 ± 3.6	169.3 ± 8.4	157.5 ± 6.2	174.9 ± 3.1
Compression test - high loading condition (force: 1650 N) with insoles								
Disp [mm]	14.9 ± 0.3	13.7 ± 0.4	9.8 ± 0.3	10.5 ± 0.6	19.6 ± 0.7	19.1 ± 0.7	16.6 ± 0.6	16.7 ± 0.8
Energy [N*mm]	607.1 ± 27.6	625.7 ± 15.2	619.4 ± 16.2	567.1 ± 11.8	658.6 ± 7.8	704.9 ± 21.9	631.9 ± 23.6	588.6 ± 14.4
Compression test - high loading condition (force: 1650 N) without insoles								
Disp [mm]	11.2 ± 0.4	11.2 ± 0.3	7.3 ± 0.3	9.1 ± 0.9	16.1 ± 0.3	15.7 ± 0.6	12.9 ± 0.3	12.9 ± 0.4
Energy [N*mm]	688.3 ± 33.8	672.6 ± 27.4	662.5 ± 11.8	608.9 ± 17.4	730.4 ± 12.4	754.9 ± 36.2	737.9 ± 42.9	706.8 ± 24.5
Impact test with insoles								
Disp [mm]	9.6 ± 0.4	8.9 ± 0.3	7.1 ± 0.2	8.1 ± 0.3	9.5 ± 0.3	8.2 ± 0.2	8.7 ± 0.4	9.3 ± 0.3
Energy [N*mm]	824.2 ± 28.6	798.2 ± 18.6	1090.1 ± 44	1224.5 ± 32.7	708.1 ± 8.3	714.1 ± 22.4	753.5 ± 15.3	758.9 ± 22
Impact test without insoles								
Disp [mm]	7.6 ± 0.3	7.8 ± 0.4	6.9 ± 0.1	7.6 ± 0.3	9.2 ± 0.4	8.9 ± 0.8	7.1 ± 0.2	7.3 ± 0.1
Energy [N*mm]	943.6 ± 45.4	1064.9 ± 5	1531.7 ± 33.4	1560.9 ± 54.5	894.3 ± 22.2	884.4 ± 21.8	938.6 ± 35.9	909.3 ± 13.9

The calculated Spearman rank-order correlation coefficient can be seen in Table 3. Regarding the tests without the insoles for the compression tests with both loading conditions, high correlations were found between t_{F1} and Disp and between F_{VGRF} and Disp for both tested areas (FA and HA). High correlations for the tests at the FA were found for the compression tests with both loading conditions between t_{F1} and energy as well as between F_{VGRF} and energy. A high correlation was found between the MPA and energy for the compression test with a low loading condition at the HA. For the impact tests at the FA, high correlations were found between F_1 and Disp, the MPA and

energy, and the MPF and energy as well as the LR and energy. High correlations between t_{F1} and Disp as well as F_{VGRF} and Disp were found for the impact tests at the HA. The Mann–Whitney U-test reported no significance for any correlation of the measurements.

For the tests with insoles, high correlations were found between t_{F1} and Disp as well as F_{VGRF} and Disp at the FA for the compression tests with both loading conditions as well as the impact test. For the compression test with the low loading condition at the FA, high correlations were found between t_{F1} and energy, whereas no correlations were found for the HA. For the compression tests with the high loading condition at the HA, high correlations were found between t_{F1} and Disp as well as energy, and between F_{VGRF} and Disp. For the impact tests, high correlations between the MPF and energy as well as between the LR and energy were found for the FA as well as the HA. Furthermore, high correlations were found between the MPA and energy for the impact tests at the HA. The Mann–Whitney U-test reported no significance for any correlation of the measurements.

Table 3. Spearman rank-order correlation for the relation between the results of the BIO and the MATs carried out with as well as without the insoles. Bold numbers indicate a high correlation coefficient (>0.95).

	Disp				Energy			
	FA		HA		FA		HA	
Parameter	without	with	without	with	without	with	without	with
Compression test—low loading condition (force: 400 N)								
MPA	0.767	0.767	0.767	**0.967**	0.833	0.767	**0.967**	0.767
MPF	0.7	0.7	0.7	0.9	0.867	0.7	0.9	0.8
F_1	0.8	0.8	0.8	0.933	0.867	0.867	0.933	0.833
t_{F1}	**0.992**	**0.992**	**0.992**	0.825	**0.9583**	**0.9583**	0.825	0.825
I_{75}	0.7	0.7	0.7	0.767	0.833	0.833	0.767	**0.967**
F_{VGRF}	**1**	**1**	**1**	0.867	**0.967**	0.933	0.867	0.767
LR	0.7	0.7	0.7	0.9	0.867	0.7	0.9	0.8
Compression test—high loading condition (force: 1650 N)								
MPA	0.767	0.767	0.7	0.767	0.7	0.8	0.8	0.767
MPF	0.7	0.7	0.667	0.7	0.667	0.767	0.767	0.7
F_1	0.8	0.8	0.767	0.8	0.767	0.9	0.9	0.867
t_{F1}	**0.992**	**0.992**	**0.992**	**0.992**	**0.992**	0.875	0.875	**0.9583**
I_{75}	0.7	0.7	0.767	0.7	0.767	0.933	0.933	0.833
F_{VGRF}	**1**	**1**	**0.967**	**1**	**0.967**	0.833	0.833	0.933
LR	0.7	0.7	0.667	0.7	0.667	0.767	0.767	0.7
Impact test								
MPA	0.933	0.767	0.767	0.767	**0.967**	0.9	0.833	**0.967**
MPF	0.833	0.7	0.7	0.8	**1**	**0.967**	0.933	**1**
F_1	**0.967**	0.8	0.8	0.7	0.9	0.8	0.767	0.9
t_{F1}	0.875	**0.992**	**0.992**	0.892	0.692	0.725	0.725	0.692
I_{75}	0.8	0.7	0.7	0.7	0.9	0.833	0.9	0.9
F_{VGRF}	0.9	**1**	**1**	0.9	0.7	0.733	0.7	0.7
LR	0.83	0.7	0.7	0.8	**1**	**0.967**	0.933	**1**

4. Discussion

The results of the BIO as well as of the MATs were found to be in the range of the values reported in previous studies [11,13,15–17]. Further, the results show 19 high positive linear correlations for the Spearman rank-order correlation coefficient for the tests without the insoles (Table 1) and 17 high positive linear correlations for the tests with the insoles (Table 2). None of the results show any negative correlation as well as no correlation (i.e., Spearman rank-order correlation coefficient = 0). Hence, $H1_0$ cannot be verified, since (even though not significant) correlations were found for the measurement without insoles. Further, as the Mann–Whitney U-test also reported no

significance for any correlation of the measurements without the insoles, $H2_0$ cannot be confirmed either. Interestingly, more high correlations were found between the MATs without insoles and the BIO than between the MATs with insoles and the BIO.

Another interesting fact is that for the compression tests with the low loading conditions, high correlations were found between the BIO and more parameters of the MATs than for the high loading condition, especially with the insoles. However, the results indicate that with the analysed parameters of the impact test, conclusions can be drawn to even more parameters of the BIO (e.g., all except for the I_{75} for the measurements without insoles). Therefore, including impact tests in the development process is supposedly more meaningful than compression tests.

5. Conclusions

The aim of this study was to find possible correlations between the variables measured with the BIO and several MATs, hoping that in the future it could be sufficient to exclusively carry out selected types of tests and deduce the results of others. As this study is limited to only four different pairs of running shoes, the results can just be seen as a first new approach. However, the findings of this study are that (a) impact tests can provide more information only about the supposed results of the BIO than compression tests and (b) carrying out MATs without insoles leads to more correlations with the parameters of the BIO.

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