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EVALUATION OF FOOTFALL-INDUCED VIBRATIONS AND THEIR IMPORTANCE IN A BIOMECHANICS LABORATORY

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Abstract: *The ground reaction forces of the footfall are usually measured in biomechanics laboratories, using a force plate. The accelerations of the floor, in which the force plate is embedded, have to be limited, as they have a major influence on the accuracy of the force measurements. A floor designed to accommodate a force platform in a biomechanical laboratory of the University Hospital in Tübingen, Germany, has been investigated for footfall induced vibrations, in order to determine their influence on the precision of the force plate measurements. For that, field measurements as well as finite element analysis have been performed. As a result, the measuring error of the force plate can be computed for diverse scenarios.*

Key words: *Floor vibrations; Force plate; Footfall induced vibrations*

1. Introduction

1.1. Gait analysis

Gait laboratories serve in orthopaedic hospitals for the study and analysis of the human gait with medical purposes. The investigation of the motion sequences of living beings is a topic of biomechanics. The biomechanical gait analyses have diverse possible applications in medicine, such as an exact analysis of motion restrictions in diagnosis, or the verification of rehabilitation measures by means of objective criteria in the field of orthopaedics rehabilitation [5, 11]. Biomechanical procedures are also used in the sport science for the motion analysis and the performance diagnostics of athletes.

The measurements in gait laboratories can be performed employing different, complementary systems, such as video recordings with subsequent computer analysis, force measurements using force plates, or neurological methods of the electromyography (measurement of the electrical muscle activity). The measurements of the time dependent ground reaction forces of the footfall are carried out using force plates embedded in the laboratory floor. The measurement of the force can be done piezoelectric or by the use of strain gauges. In the case of piezometrical measuring technique, the piezoelectric effect (electrical charge of crystals during mechanical loads) is used for force measurements. The force platforms based on the piezometrical principle have a very high measuring accuracy and an extremely wide measuring range. They will be considered in the

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following. The reaction force of the plate in response to the footfall load is measured as three-dimensional vector.

It should also be pointed out, that special insoles for shoes were developed, which measure the local pressure distribution at the bottom side of the foot. They have already been used in structural dynamics applications [13].

The force platforms have to be embedded vibration-free, as their accuracy is affected by the accelerations of the underfloor. The guidelines for vibrations in hospitals refer mainly to steel constructions and the negative impact on the comfort of the persons [3, 4]. Therefore separate research has been done in the present case.

1.2. Biomechanics Laboratory at the University Hospital in Tübingen

The biomechanics laboratory is located in the new building of the Health Centre at the University Hospital in Tübingen, which has been built between 2011 and 2012 (Figure 1).

The gait laboratory is situated in an open space area, used for office as well as for therapeutical purposes. The paper describes the investigation of the influence of floor vibrations, induced by footfalls in the office section, on the accuracy of the simultaneous measurements with the force plate. For this, field measurements and finite element analysis have been done.

Fig. 1. *Health Centre Tübingen: Building and Biomechanics Laboratory*

2. Force plate

2.1. Construction

Force plates serve in biomechanics laboratories for the precise measurement of the ground reaction forces in response to the human footfall. They basically consist of a cover plate made from steel, aluminium or glass and the underlying supports with the piezometrical sensors (Figure 2). Firmly fixed plates are usually embedded in a planned indentation of the floor, using an installation frame. In the present case, a Kistler force platform of the type 9287 CA [7], with a total mass of 25 kg, has been used. The cover plate has a mass 20.7 kg [8].

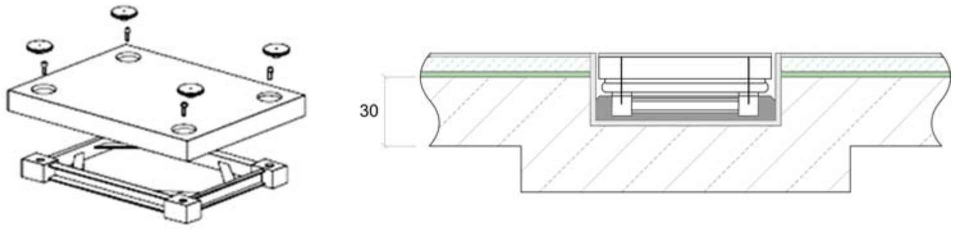

Fig. 2. *Force plate and installation frame in the floor indentation*

Besides the abovementioned stationary force plates, which are embedded in the laboratory floor, there are also portable solutions available (Figure 3), which may facilitate methods of force measurements that can be applied out into the field, offering a comparable measurement performance to mounted force plates.

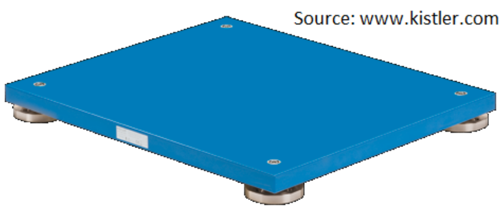

Fig. 3. *Portable force plate*

2.2. Force measurement

The force plates measure the ground reaction forces induced by the footfall of the subjects. All the three force components are determined, namely the vertical and the two horizontal, parallel to the plate edges. Usually, a walking and running path parallel to the plate edges is adopted, so that the force components are parallel, respectively perpendicular to the direction of movement. Figure 4 shows an example of a force measurement for a subject weighting G = 0.87 kN, walking with the step frequency f_s = 2 Hz.

2.3. Measuring precision

The acceleration of the floor, in which the force plate is embedded, respectively on which the portable platform is deployed, alter the measuring signal. Therefore the floor acceleration has to be limited, in order to keep a low measuring error. The tolerable measuring error is usually assumed to 1% of the maximal measured force.

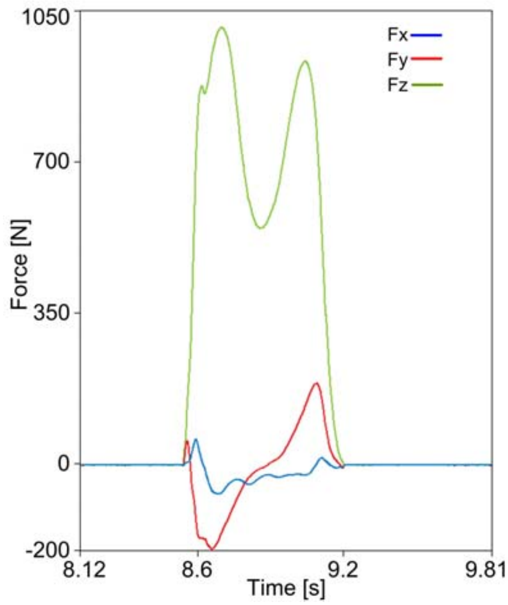

Fig. 4: *Force time history measured with a force plate (G = 0.87 kN, f_s = 2Hz)*

The vertical eigenfrequency of the used force plate is very high, about 500 Hz, due to the very stiff bearing elements. Therefore the self-vibration of the plate can be excluded, assuming that it was installed properly. Hence the measuring error can be determined from the mass force of the cover plate.

$$p = \frac{m_{Pl} \cdot a_g}{F_{Pers}} \qquad (1)$$

where,
p = measuring error;
m_{Pl} = mass of the cover plate;
a_g = acceleration of the floor;
F_{Pers} = maximal measured force.

The limit value of the underfloor acceleration for a given measuring accuracy is

$$a_g = \frac{F_{Pers} \cdot p}{m_{Pl}} \qquad (2)$$

Assuming a tolerable measuring error of 1% and a static load due to a subject with a weight force of 0.4 kN, a limit value of the acceleration of 0.1 m/s² is obtained for an assumed mass of the cover plate of 40 kg. For a cover plate weighting 20 kg, the maximal tolerated acceleration is 0.2 m/s².

The floor acceleration can be caused by self-excitation of the subject during the measurement or by external excitations. In both cases the force to be measured is proportional to the weight of the subjects, $F_{Pers} = \overline{\alpha} \cdot G$. For the coefficient $\overline{\alpha}$ a lower limiting value is to be used. This can be chosen to 1.0 for static load (standing), 1.1-1.2 for walking [6], 1.8-2.2 for running and about 3.0 for jumping [12]. Hence the percental measuring error for an external excitation inducing the floor acceleration a_{g0} is

$$p = \frac{m_{Pl} \cdot a_{g0}}{\overline{\alpha} \cdot G} \qquad (3)$$

For a self-excitation, the maximal acceleration of the floor is proportional to the weight G of the subject. Employing the acceleration normalized to the subject weight, $\overline{a} = a_g / G$, the percental error of measurement is obtained to

$$p = \frac{m_{Pl} \cdot \overline{a}}{\overline{\alpha}} \qquad (4)$$

Equation 5 gives the measuring error for the case when both the external and the self-excitation occur at the same time. A random distribution of the maxima for both acceleration time histories is assumed.

$$p = \frac{m_{Pl}}{\overline{\alpha}} \cdot \sqrt{\left(\frac{a_{g0}}{G}\right)^2 + \overline{a}^2} \qquad (5)$$

3. Investigations in the University Hospital Tübingen

3.1. Generals

For the investigation of the measuring precision of the force platform, field measurements and numerical simulations have been carried out.

3.2. Loading scenarios

The chosen loading scenarios for this investigation describe typical situations during force measurements. For the case of vibrations caused by external excitation, the following scenario was considered:

- People in the room: 5 people, weighting 0.8 kN each, are walking in the room.

Three scenarios for the self-excited vibrations have been investigated:

- Walking: The subject is walking on a predefined path, including the force platform.
- Running: The subject is running on predefined path, including the force platform.
- Vertical Jump: The subject stands on the force plate, bends his knees and performs a jump.

The weight of a subject may vary between 0.45 kN (light female runner) and 1.20 kN (1.90m – male runner). However, typical values are 0.70-0.80 kN.

These scenarios underlie the numerical simulations as well as the vibration field measurements.

4. Calculation procedure

4.1. Generals

Footfall induced vibrations can be computed using time integration methods. Simplified procedures, which assume only one eigenmode, are inapplicable here, because in the case of continuous slabs, many adjacent eigenfrequencies occur, whose eigenmodes are relevant for the vibration response.

4.2. Loading models

The load generated by a single walking or running subject can be described by load functions for every step (as in Figure 4) or simplified, using a continuous, time dependent, single load. Werkle [15], Butz [2] and Zivanovic [17] give overviews over various approaches for human-induced walking and running loads.

In the following, the time dependent load is represented as a Fourier series:

$$F(t) = G + \sum G \cdot \alpha_j \cdot \sin\left(2\pi jt \cdot f_s - \varphi_j\right) \quad (6)$$

Here f_s is the step frequency. The subject weight was assumed to be 0.8 kN. The Fourier-coefficients α and φ have been determined by different authors. Table 1 shows values for walking and running according to Bachmann [1].

Furthermore the heel-strike effect is relevant for the vibration response of high frequency floors [10]. However, this can be neglected in the present investigation.

Values of α *and* φ *coefficients for walking and running* Table 1

		Bachmann – Walking	Bachmann – Running
j	f_s	1.5 – 2.5 [Hz] (Average value 2 Hz)	2.0 –3.0 [Hz]
1	α_1	0.4 for $f_s \leq 2\ Hz$ $0.4 + 0.1 \cdot (f_s - 2) / 0.4$ for $2.0\ Hz \leq f_s \leq 2.4\ Hz$ 0.5 for $f_s \geq 2.4\ Hz$	1.6
2	α_2	0.1	0.7
3	α_3	0.1	0.2
1	φ_1	0	0
2	φ_2	π / 2	π / 2
3	φ_3	π / 2	π / 2

For the scenario "Vertical Jump", the following idealized force-time history, developed by Werkle et. al. [16], has been used:

$$F(t) = G \cdot \left(1 + \frac{1}{e^{\alpha \cdot t_2}} \cdot \left(e^{\alpha \cdot t} \cdot \sin\left(\frac{2 \cdot \pi}{T_0 - \beta \cdot t} \cdot t\right)\right)\right), \quad for \quad t \leq \frac{3 \cdot T_0}{2 + 3 \cdot \beta}$$

$$= G, \quad for\ t \geq \frac{3 \cdot T_0}{2 + 3 \cdot \beta}, \quad with \quad t_2 = \frac{3 \cdot T_0}{4 + 3 \cdot \beta} \quad (7)$$

$\alpha = 8.7$, $\beta = 2$ and $T_0 = 2.1$ (Figure 5). The first peak corresponds to the take-off phase, while the second one corresponds to the landing phase.

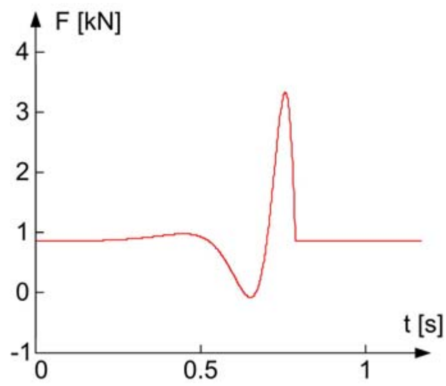

Fig. 5. *Force time history for vertical jump*

All the load models are valid for a single person. For an excitation induced by multiple subjects, the acceleration obtained for "walking" of a single person may be multiplied by the factor $m = \sqrt{n}$, where n means the number of the persons.

4.3. Structural model

The floor of the biomechanics laboratory has been completely reproduced in a detailed finite element model and a subsequent computation with the FE-Program Sofistik (2010) has been performed. The finite element model consists of 6615 rectangular plate-elements, containing 40725 degrees of freedom [9]. The integration of the modal equations has been made using a Mathcad worksheet [14]. The reinforced concrete floor has a thickness of 30 cm and is elastically clamped in the outer walls. The floor panels present spans between 8 and 11 m. The damping was assumed to be 1%.

4.4. Numerical computation of the human-induced vibrations

The computations in time domain have been performed using a modal analysis. Table 2 shows the measured and computed eigenfrequencies of the floor and Figure 6 shows some relevant eigenmodes.

Eigenfrequencies of the floor Table 2

Eigenmode	Measured [Hz]	FE-Analysis [Hz]
1	7.27	7.32
2	7.63	7.68
3	8.07	8.21
4	11.55	11.62
5	12.78	12.87
6	13.68	13.52
7	13.93	13.96
8	16.30	16.19
9	17.32	17.17
10	18.90	18.58
11	19.62	19.50

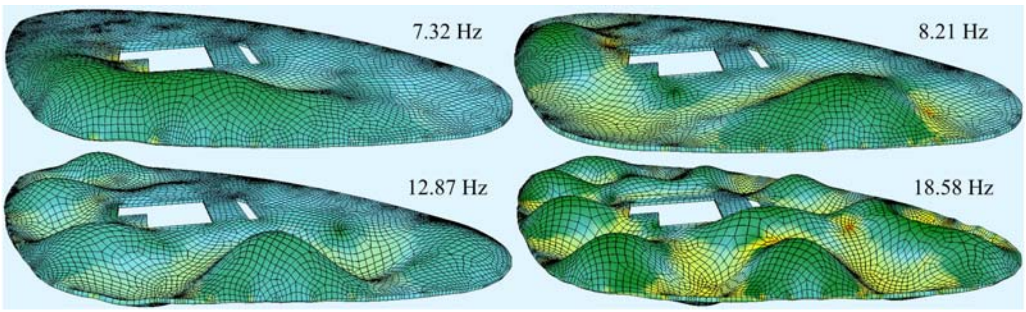

Fig. 6. *Eigenmodes*

A walking and running path has been predefined for the human-induced vibrations. It corresponds approximately to the path used by the subjects in biomechanical measurements. The force plate is situated on this path.

Figure 7 shows typical acceleration time histories of the floor for the scenarios walking, running and vertical jumping. The plots correspond to the location point of the force plate. The maximal accelerations for various walking and running frequencies are shown in Figure 10.

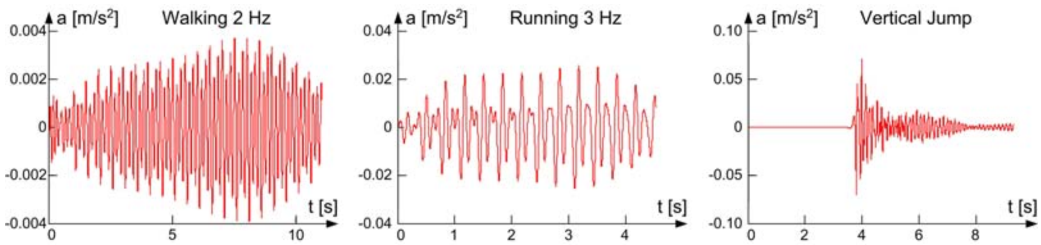

Fig. 7: *Time histories for walking, running and vertical jump of a subject (FEM)*

5. Vibration measurements

Two stages of the construction have been investigated experimentally: the raw concrete floor and the final state of the finished floor, including a layer of sound insulation and a floating floor screed.

5.1. Eigenfrequencies

The eigenfrequencies of the floor for both stages have been determined through measurements of ambient vibrations and subsequent Fourier analyses. A good correlation between the eigenfrequencies of the two measured construction stages could be observed. The results are shown in Table 2.

5.2. Footfall induced vibrations

The vibrations caused by subjects performing the abovementioned loading scenarios have been measured using extremely sensitive seismic accelerometers. The subjects were wearing sport shoes, which are typical for the activities in the biomechanics laboratory. For each scenario, acceleration time histories at different relevant points were recorded. The results were normalized to a subject weight of 0.8 kN. Two typical time histories of a point corresponding to the force plate are plotted in the Figure 8 for the unfinished floor and in Figure 9 for the finished floor.

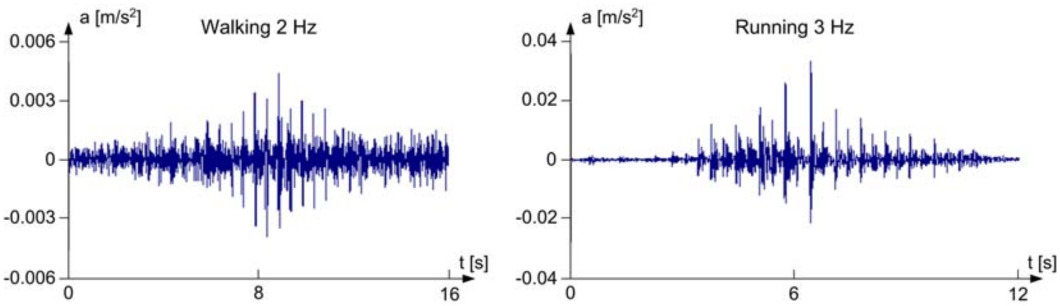

Fig. 8. *Measured time histories for walking and running (raw concrete floor)*

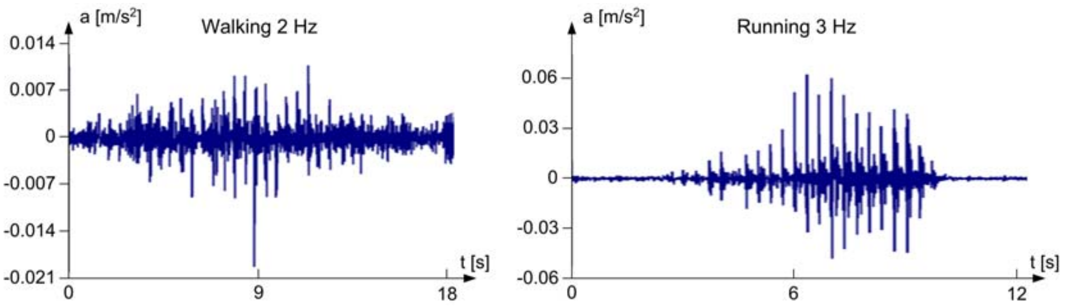

Fig. 9. *Measured time histories for walking and running (finished floor)*

Figure 10 shows the maximal accelerations for walking and running at different step frequencies for both measured construction stages, as well as for the finite element analysis, which was conducted only for the unfinished floor. Excepting the resonant effects due to the higher Fourier terms in the computed accelerations for running, a good correlation between the measurements performed on the raw concrete floor and the corresponding computations can be observed. However the accelerations of 0.005 m/s^2 for walking and 0.03-0.06 m/s^2 for running are quite low. The highest accelerations in this stage of construction, of about 0.07 m/s^2, occur as a response of the vertical jump.

The measurements in the final stage of the finished floor revealed much higher accelerations than the ones of the raw concrete floor for the same investigated scenarios. Possible causes for this may be the local deformation of the soft sound insulation layer or resonant effects of the floating floor over the sound insulation. Research on these effects is in progress.

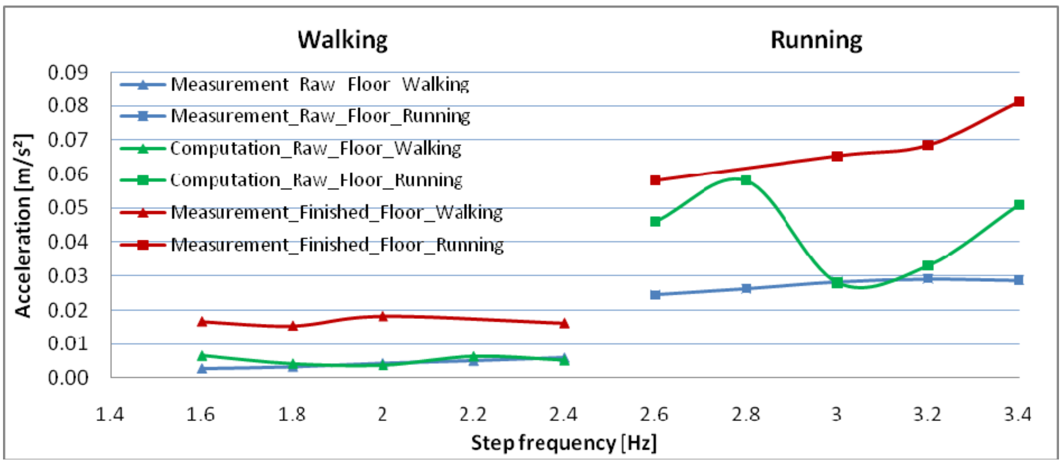

Fig. 10. *Maximal Acceleration of the force plate – computation and measurements*

6. Measurement precision of the force platform

The measuring error of the force plate can be determined according to Equation 5. As the plate used in the biomechanics laboratory at the University Hospital in Tübingen is embedded directly in the concrete deck, the corresponding computed and measured accelerations for the first construction stage will be employed. The weight of the subject was conservatively assumed to 0.5 kN, the mass of the cover plate to 20.7 kg while the values of the coefficient $\overline{\alpha}$ are considered to 1 for walking, 2 for running and 3 for vertical jumping. Furthermore, it was started from the premise that both self and external excitation occur at the same time.

According to Equation 5, the measuring error for all the considered scenarios is under 0.1%. Even when parameter variations due to model uncertainties (induced, for instance, by the shoe type) are considered, the measuring error remains in per mille domain and thereby very low.

If a portable force measuring plate (assumed to have the same mass as the fixed one) would be put into use in the investigated biomechanics laboratory, the measuring errors would be also lower than the tolerable error. However, special attention is required for the vibration analysis in this case, as the maximal accelerations usually occur in the form of single peaks, which are likely to be much higher than the average envelope of the time history (see Figure 9 left).

7. Conclusions

The measuring error of force platforms in biomechanics laboratories can be computed based on experimental and numerical investigations. Scenarios and formulas for determining the measuring error have been proposed. It was shown, that the measuring precision of the force plate from the biomechanical laboratory at the University Hospital in Tübingen, Germany, is not significantly influenced by the human induced vibrations of the floor.

Further researches in the numerical simulations of the human-induced vibrations of concrete floors are needed, in order to obtain an accurate method for assessing the effects of the floor finishing accurately.

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