Motek
a DIH brand

QUALITY OF TREADMILL EMBEDDED FORCE PLATES FOR GAIT ANALYSIS

Authors: Lars Aarts, Selma Papegaaij, Frans Steenbrink, Peter Martens

WHITE PAPER

June 2018

QUALITY OF TREADMILL EMBEDDED FORCE PLATES FOR GAIT ANALYSIS

Authors:
Lars Aarts, MSc; Applied Researcher
Selma Papegaaij, PhD, PT; Clinical Applications & Research Manager
Frans Steenbrink, PhD, PT; Head of Clinical Applications & Research
Peter Martens, PhD; Head of Development

INTRODUCTION

Gait analysis is used for both fundamental human movement research as well as clinical purposes with the aim to diagnose, plan and evaluate interventions. Gait analysis was traditionally performed during overground walking using floor embedded force plates to record ground reaction forces during single steps. In the last decades the use of instrumented treadmills demonstrated several advantages with respect to overground methods.[1–4] A treadmill requires less space and allows for continuous recording of gait data, thus improving measurement efficiency and data reliability.[5,6] Also, gait analysis can be enriched by simulating real life challenges using virtual/augmented reality or sudden balance perturbations. Accurate measurement of ground reaction force and Center of Pressure (CoP) is essential for reliable gait analysis as errors will affect joint moments. Therefore, the goal of this white paper is to provide an overview of the force plate characteristics that can influence gait data. These characteristics will then be evaluated for the force plates in an instrumented treadmill (Motek's R-Mill (M-Gait, GRAIL, CAREN)) based on the protocol proposed by Sloot et al. (2015)[7].

ACCURACY

Force plate accuracy shows to what extend the recorded forces and CoP exerted on the walking surface match the 'actual' forces and CoP exerted by a subject. For forces, the accuracy can be determined by comparing the measured force to a known load applied by calibrated weights.[3,4,8]
The accuracy of the CoP can be determined by comparing the calculated CoP with the known locations of the applied load,[3,4,9] potentially determined by a motion capture system.[2,8,10–12]
Force and CoP accuracy measurements can also be combined using an instrumented pole.[7,10,13] Such a pole contains a force transducer to measure the applied force, as well as markers tracked by a motion capture system to determine the direction and location of the force.[7]
Obtaining data with an inaccurate force plate will, when combined with motion capture data, lead to errors in kinetic parameters such as joint moments and joint powers. Inaccuracy can be the result of a bad design as well as insufficient calibration.

LINEARITY AND HYSTERESIS

Perfect linearity means that if the applied force is multiplied by a given factor, the data recorded by the force plate is multiplied by the same factor. Non-linearity of a force plate is expressed as the maximal deviation from a linear regression fitted through the measured forces versus the known loads.[2,7] High non-linearity means that forces are not accurate over the entire force plate's measurement range, causing similar errors as an inaccurate force plate.
Hysteresis is the difference in recorded forces when loading towards a certain force and unloading towards the same force.[7] A force plate with a high amount of hysteresis will lead to over- or underestimation of the forces during either loading or unloading, again affecting kinetic data accuracy.

CROSS-TALK

Cross-talk is the force measured in a sensor while the force is not applied in the direction of that sensor or on the force plate where the sensor is not attached to. Cross-talk may thus occur within or between force plates. An example of within force plate cross-talk is when the horizontal sensors measure some force even though a pure vertical force is applied. Between force plates cross-talk means that forces are measured while forces are only applied to another (adjacent) force plate.

NATURAL FREQUENCY

The natural frequency is the frequency in which the force plate will vibrate when no external forces are exerted. When a force with this specific frequency is applied, the force plate will start resonating, resulting in inaccurate force recordings. Some authors state that the natural frequency of the force plate has to be five times higher than the highest frequency in your force signal.[14] According to others it is only important that this natural frequency is higher than the highest frequency present in the exerted force, to avoid amplification by the mechanical system.[3,15,16] In any case, it is important to know the natural frequency of the force plate as well as the highest frequency to be expected in the data during recording in order to understand the source of possible noise in the data. To determine the natural frequency of a force plate, the vibrations of the force plate are analyzed after an external impulse to the plate. This impulse is applied by either tapping the plate with a mallet or (instrumented) hammer,[1,2,7,8,15] or dropping a wooden ball on the plate.[4,9] The vibrations are either measured by attaching an accelerometer to the plate or obtained from the force sensors.
Besides different methods to provide an impulse to the force plate, different ways of analyzing the response signal are found in literature. Natural frequency can be calculated from the time it takes to complete a given number of oscillation cycles[3,8] or by analyzing the frequency content of the vibration signal, using a fast Fourier transform.[1,2,4,9] Instead of determining the impulse response, it is also possible to estimate the frequency response function or transfer function. These measures compare the output signal to the input signal and therefore requires measurement of the input signal, for example by using an instrumented hammer.[7] The use of different methods to determine the natural frequency implies that results presented in literature cannot readily be compared.

DRIFT

Drift means that the measured force is changing over time when the external load is kept constant. Usually the drift is determined by measuring an unloaded force plate over a long time (e.g. 30 minutes) and determining the linear regression between force and elapsed time.[1,7] Error caused by drift can be handled by frequently resetting the calibration of the force plate (zero-leveling) before and/or in between measurements.

NOISE

Noise in the force signals will occur from both electrical as well as mechanical sources. The electrical noise is usually determined by comparing the force signal when the motor is turned on with the belts stationary to the signal when the motor is turned off.[2,4,7] Mechanical noise can be determined from differences in noise levels between stationary belts and running belts,[2,8] and usually increases with increasing belt speeds.[4,7,17]

METHODS

Measurements based on the protocol by Sloot et al. (2015)[7] were performed on an R-Mill ready for distribution to determine the force plate characteristics.

ACCURACY

Five seconds recordings of a calibrated weight (313N) placed at 55 different positions per force plate were captured (grid of 5 positions in medio-lateral direction and 11 positions in anterior-posterior direction). A reflective marker was placed in the center of the weight to be able to measure the position using a Vicon Motion Capture system. Both force and motion data were low-pass filtered at 20Hz using a second order bi-directional Butterworth filter. Force error was defined as the RMSE between the vertical force measured and the known vertical force applied. To determine the CoP accuracy, a correction for the misalignment between the reference frame of the force plate and the motion capture data has to be performed. Therefore, the average positions are subtracted from the original data to align the origins of the reference frames in the horizontal plane. Subsequently, an optimization method was used which rotated the motion capture data around the vertical axis to minimize the maximum CoP error. CoP error was then defined as the root mean square error (RMSE) between the position determined by the force plate and the marker position.

LINEARITY AND HYSTERESIS

Ten seconds recordings of calibrated weights placed in the middle of the force plate were captured on both force plates. Mass was first increased from zero to 90kg in steps of 15kg, and subsequently decreased back to zero using the same step size.

All force data were low-pass filtered at 20Hz using a second order bi-directional Butterworth filter. Non-linearity was defined as three standard deviations (to exclude outliers) of the differences between measured force and a linear least squares fit through all the measured forces against applied forces. Hysteresis was defined as the maximal differences between the third order least squares fits of the loading (increasing mass from 0 to 90kg) and unloading (decreasing mass from 90 to 0kg) data.

CROSS-TALK

To determine cross-talk, data from the linearity and hysteresis measurements was used. Cross-talk within force plates was defined as the forces measured in the horizontal plane of the same plate as a percentage of the measured vertical force. Cross-talk between force plates was defined as the measured forces in the unloaded plate for all directions as a percentage of the measured vertical force on the loaded plate. For each direction the highest percentage found for any of the weight is reported in Table 1.

NATURAL FREQUENCY

The force plate was hit fifteen times with an instrumented hammer in each direction. Vertical hits were applied to the middle of the force plate on top. Anterior-posterior hits were applied to the back roll of the treadmill. Medio-lateral hits are applied to the side of a 15kg mass placed on the middle of the force plate.

For each hit, raw hammer and sensor data for the first second after each hit (hammer data > 2.0) were selected. Hammer data was zeroed for all values below 0.1. Sensor data was filtered with an exponential window, which means the data was multiplied with a function that exponentially decreases from one to zero over one second. The transfer function was estimated as the cross power spectral density of hammer and sensor data divided by the power spectral density of the hammer data. For each sensor, the transfer function was averaged over all hits in the corresponding direction. The natural frequency of the force plate was defined as the lowest frequency with a peak in the transfer function in one of the sensors in the corresponding direction.

DRIFT

After letting the sensors warm up for over an hour, a 30 minute recording of empty force plates was captured. All force data were low-pass filtered at 0.1Hz using a second order bi-directional Butterworth filter. Drift was defined as the slope of the linear least squares regression line of force against time.

NOISE

Noise levels were captured for 10 seconds with the motor off, motor on, and with the belts running at three different speeds (0.28, 0.70, and 1.39 ms^{-1}). Additionally, a 30 seconds trial with a subject walking at 1.39 ms^{-1} was recorded.

Noise was defined as three times the standard deviation of the measured forces. Signal to noise was determined as the root mean square (RMS) of the fast Fourier transform (FFT) of the walking trial divided by the RMS of the FFT for the unloaded trial with the belts running at 1.39 ms^{-1}. Only data between 0 and 20Hz was included in this analysis. Noise was determined for the raw data as well as for data which was low-pass filtered at 20Hz using a second order bi-directional Butterworth filter.

RESULTS

Table 1 shows an overview of all characteristics of the R-Mill. For CoP and force accuracy, mean error and standard deviation are provided.

Table 1. Characteristics of the force plates embedded in the Motek R-Mill. Error sizes are provided in the given units for each force plate in medio-lateral (ml), anterior-posterior (ap) and vertical (vert) direction. In case of CoP and force accuracy, mean and standard deviation values are provided. For noise and signal to noise ratio, values for both raw and 20Hz low pass filtered data are provided.

Error source	Condition	Direction	Left	Right
Force accuracy [N / %]		vert	1.5 (0.2) / 0.44 (0.08)	0.7 (0.2) / 0.18 (0.06)
CoP accuracy [mm]		ml	1.6 (0.9)	0.9 (0.5)
		ap	1.8 (0.7)	1.8 (0.8)
Non-linearity [N / %FSO]		vert	0.13 / 0.0009	0.14 / 0.0010
Hysteresis [N / %FSO]		vert	0.07 / 0.0005	0.07 / 0.0005
Cross-talk (maximum values)	Between plates	ml	0.026 %	0.069 %
		ap	0.194 %	0.052 %
		vert	0.109 %	0.145 %
	Within plate	ml	0.032 %	0.135 %
		ap	0.245 %	0.066 %
Natural frequency [Hz]		ml	31	31
		ap	32	31
		vert	28	29
Drift [N/hour]		ml	-0.0218	-0.0442
		ap	-0.0878	-0.0974
		vert	-0.0800	-0.0199
Noise [N] (Raw / filtered)	Motor off	ml	02.29 / 00.64	02.30 / 00.55
		ap	01.73 / 00.45	01.56 / 00.39
		vert	02.81 / 00.68	02.85 / 00.78
	Motor on 0 ms-1	ml	15.12 / 01.95	13.35 / 01.89
		ap	11.28 / 01.43	11.07 / 01.42
		vert	19.28 / 02.32	19.30 / 02.36
	Motor on 0.28 ms-1	ml	10.42 / 01.88	09.55 / 01.62
		ap	07.65 / 01.42	07.49 / 01.50
		vert	15.29 / 02.66	15.83 / 02.68
	Motor on 0.70 ms-1	ml	14.39 / 01.67	14.34 / 01.46
		ap	08.13 / 01.12	07.88 / 01.14
		vert	18.26 / 02.16	21.18 / 02.51
	Motor on 1.39 ms-1	ml	14.87 / 02.05	14.54 / 01.89
		ap	10.75 / 01.72	10.34 / 01.66
		vert	14.98 / 02.55	15.69 / 03.13
Signal to noise ratio (Raw / filtered)		ml	108 / 130	116 / 144
		ap	231 / 272	224 / 272
		vert	1181 / 1471	916 / 1154

DISCUSSION

This paper provides an overview of the most important treadmill embedded force plate characteristics as well as an overview of all those characteristics measured on Motek's R-Mill.

The force error of the R-Mill force plates is lower than or comparable to the force error found in other systems,[4,7,8,10,18] as is the CoP error.[2,3,8,10] It is important to note that a misalignment in the reference frames of the force plate and motion capture system may increase the CoP error with respect to the motion capture data, causing errors in joint moments. Therefore, careful calibration procedures or a motion capture transformation optimization are required.[19] Errors due to non-linearity and hysteresis were substantially smaller than the force error and will therefore not have a significant contribution.

Cross talk levels in the R-Mill between as well as within plates are generally lower than cross talk values found in literature, which ranged from 0.2 to 2.9%.[1,2,4,9] Only the crosstalk in anterior-posterior direction within the left plate was 0.245%, which is just above the lowest value found in literature.[9]

Natural frequencies of the R-Mill force plates were lower than usually found in overground force plates, as well as than those found in other treadmill embedded force plates.[1,3,4,8,9] However, they were higher than in the only other treadmill capable of platform perturbations (used to assess fall risk and train postural responses) of which the natural frequency was reported.[20] Moreover, several studies found that the majority of the frequency content of the force plate signals during gait is below 10Hz[3,21–23] and additionally, Kram et al. (1998) found that for running 99% of the power was contained below 10Hz for the vertical signals. For horizontal signals more than 98% of the power was contained below 17Hz.[3] Only for impact forces, which occur during initial contact, higher frequency contents were observed.[23–25] So the natural frequencies of the R-Mill are above the frequency content which can be expected during gait as has been reported in previous studies. The force plates embedded in the R-Mill are therefore suitable for measurements of gait and even running ground reaction forces, except when the user is specifically interested in impact forces or joint moments/powers during the impact phase. In that case it would be better to use floor embedded force plates.

Drift values in the R-Mill are substantially lower than values found in other treadmills,[1,8] due to the specific design of the electronics in the amplifier (ForsAmp). That this low drift can be devoted to this new amplifier becomes clear when the current drift values are compared to drift values found in an earlier version of the R-Mill, which did not contain this amplifier (4 to 36 times lower).[7] Furthermore, these values are substantially lower than the force accuracy and are therefore as good as negligible.

Noise levels substantially increased when the motor was turned on, but they did not increase further with belt speed. The noise was therefore mainly electrical, with the largest part of the noise occurring at frequencies above 20Hz. Hence filtering with a 20Hz low pass filter subsequently decreased the noise levels (Table 1). Higher,[3,10] comparable[1,4,18,20] and lower[2,8] noise levels have been found in literature.

In conclusion, the characteristics of the force plates of the R-Mill demonstrate its suitability for gait analysis. The R-Mill is capable of accurate force and CoP measurements, combined with low noise levels, a high signal to noise ratio, and almost negligible non-linearity, hysteresis and drift. The remaining error in the data is easily averaged out, since every gait cycle can be recorded.[6] Although the R-Mill was specifically designed for gait analysis, it can be used for the major portion of running analysis.

REFERENCES

1. Belli A, Bui P, Berger A, Geyssant A, Lacour JR. A treadmill ergometer for three-dimensional ground reaction forces measurement during walking. *J Biomech*. 2001;34(1):105-112. doi:10.1016/S0021-9290(00)00125-1
2. Dierick F, Penta M, Renaut D, Detrembleur C. A force measuring treadmill in clinical gait analysis. *Gait Posture*. 2004;20(3):299-303. doi:10.1016/j.gaitpost.2003.11.001
3. Kram R, Griffin TM, Donelan JM, Chang YH. Force treadmill for measuring vertical and horizontal ground reaction forces. *J Appl Physiol*. 1998;85(2):764-769.
4. Paolini G, Della Croce U, Riley PO, Newton FK, Casey Kerrigan D. Testing of a tri-instrumented-treadmill unit for kinetic analysis of locomotion tasks in static and dynamic loading conditions. *Med Eng Phys*. 2007;29(3):404-411. doi:10.1016/j.medengphy.2006.04.002
5. Monaghan K, Delahunt E, Caulfield B. Increasing the number of gait trial recordings maximises intra-rater reliability of the CODA motion analysis system. *Gait Posture*. 2007;25(2):303-315. doi:10.1016/j.gaitpost.2006.04.011
6. Papegaaij S, Steenbrink F. Clinical gait analysis: Treadmill-based vs overground. 2017;(May).
7. Sloot LH, Houdijk H, Harlaar J. A comprehensive protocol to test instrumented treadmills. *Med Eng Phys*. 2015;37(6):610-616. doi:10.1016/j.medengphy.2015.03.018
8. Tesio L, Rota V. Gait Analysis on Split-Belt Force Treadmills. *Am J Phys Med Rehabil*. 2008;87(7):515-526. doi:10.1097/PHM.0b013e31816f17e1
9. Powell MO. Testing of high speed ground reaction force treadmill for kinetic analysis for running in static and dynamic loading conditions. 2014.
10. Collins SH, Adamczyk PG, Ferris DP, Kuo AD. A simple method for calibrating force plates and force treadmills using an instrumented pole. *Gait Posture*. 2009;29(1):59-64. doi:10.1016/j.gaitpost.2008.06.010
11. Holden JP, Selbie WS, Stanhope SJ. A proposed test to support the clinical movement analysis laboratory accreditation process. *Gait Posture*. 2003;17(3):205-213. doi:10.1016/S0966-6362(02)00088-7
12. Rabuffetti M, Ferrarin M, Benvenuti F. Spot check of the calibrated force platform location. *Med Biol Eng Comput*. 2001;39(6):638-643. doi:10.1007/BF02345435
13. Lewis A, Stewart C, Postans N, Trevelyan J. Development of an instrumented pole test for use as a gait laboratory quality check. *Gait Posture*. 2007;26(2):317-322.
14. Psycharakis SG, Miller S, Psycharakis SG, Miller S. Estimation of Errors in Force Platform Data Estimation of Errors in Force Platform Data. *Res Q Exerc Sport*. 2015; 77(4):514-518. doi:10.1080/02701367.2006.10599386
15. Toso MA, Gomes HM. Dynamic Validation of a Numerical Model of Force Platform for Human Gait Analysis. In: *22nd Int Congress of Mechanical Engineering Ribeirão Preto, SP, Brazil*. ; 2013:1984-1991.
16. Willems PA, Gosseye TP. Does an instrumented treadmill correctly measure the ground reaction forces? *Biol Open*. 2013;2(12):1421-1424. doi:10.1242/bio.20136379
17. Sinitski EH, Lemaire ED, Baddour N. Evaluation of motion platform embedded with force plate-instrumented treadmill. *J Rehabil Res Dev*. 2015;52(2):221-233. doi:10.1682/Jrrd.2013.11.0244
18. Bagesteiro LB, Gould D, Ewins DJ. A vertical ground reaction force-measuring treadmill for the analysis of prosthetic limbs. *Brazilian J Biomed Eng*. 2011;27(1):3-11. doi:10.4322/rbeb.2011.001
19. Goldberg SR, Kepple TM, Stanhope SJ. In Situ Calibration and Motion Capture Transformation Optimization Improve Instrumented Treadmill Measurements. *J Appl Biomech*. 2009;25:401-406.
20. Luciani LB, Genovese V, Odetti L, Cattin E, Micera S. Design and Evaluation of a new mechatronic platform for assessment and prevention of fall risks. 2012:1-13.
21. Antonsson EK, Mann RW. The frequency content of gait. *J Biomech*. 1985;18(1):39-47. doi:10.1016/0021-9290(85)90043-0
22. Harris GF, Acharya KR, Bachschmidt RA. Investigation of spectral content from discrete plantar areas during adult gait: an expansion of rehabilitation technology. *IEEE Trans Rehabil Eng*. 1996;4(4):360-374.
23. Simon SR, Paul IL, Mansour J, Abernethy PJ, Radin EL. Peak dynamic force in human gait. *J Biomech*. 1981;14(12):817-822.
24. Gillespie KA, Dickey JP. Determination of the effectiveness of materials in attenuating high frequency shock during gait using filterbank analysis. *Clin Biomech*. 2003;18(1):50-59. doi:10.1016/j.gaitpost.2017.04.037
25. Gruber AAH, Edwards WB, Derrick TR, Boyer KA. A comparison of the ground reaction force frequency content during rearfoot and non-rearfoot running patterns. *Gait Posture*. 2017;56:54-59. doi:10.1016/j.gaitpost.2017.04.037

MOTEK
Hogehilweg 18–C
1101 CD Amsterdam
The Netherlands
https://www.motekforcelink.com/