Total Force Validation Study

OpenGo Sensor Insole (insole3)

Contact

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Legal Note and Disclaimer

Changelog

Version	Date	Changes
2.0	01.09.2021	Change product name from SCIENCE to OpenGo.
1.1	05.09.2020	Add results and discussion.
1.0	25.08.2020	Add introduction and background.
0.2	21.08.2020	Describe operation modes. Add results section.
0.1	07.07.2020	Draft of methods sections.

Contents

1 Introduction

The purpose of this study is to determine the validity of Moticon's *OpenGo Sensor Insole* (model: insole3) force output and its force zero level behavior during walking at normal speed. The study quantifies the error of total force measurements compared to the output of force plates.

The present study specifically aims to provide a basic understanding of how well the *OpenGo Sensor Insole* perform in daily routines, real life and sports settings, where no continuous interaction with the measurement system whatsoever is possible with regards to calibration or zeroing routines.

This study is the first of a series of scientific grade internal publications which provide documentation of validation projects carried out with *OpenGo Sensor Insoles*.

2 Background

Ground reaction forces (total forces) are useful in the assessment of both normal and pathologic gait patterns as a means for understanding various loading parameters as well as for training assessment purposes in sports. Historically, studies focusing on gait biomechanics in which there was a desire to assess lower extremity loading have been limited to research facilities with either cable bound in-shoe measurement systems, force plates, pressure pads, or an instrumented treadmill.

The traditional in-shoe measurement systems for scientific research purposes require cabling from the sensorized insoles to a controller box which the subject has to carry. These systems are limited in their capability to be used for daily routines or in sports due to their high complexity and costs. In addition, wires and boxes which have to be installed on the subject's body for data acquisition may reduce the subject's compliance and alter locomotion.

In 2019, Moticon has brought its third generation, fully integrated and wireless sensor insole measurement system Insole3 to the market. It enables effortless indoor and outdoor testing in almost any environment. Insole3 now allows for the simultaneous and synchronized collection of high quality plantar pressure distribution data, total forces and various spatio-temporal measures at a sampling frequency of 100 Hz. The current study verifies key performance indicators of this new product.

3 Methods

3.1 Experimental Setup

The experimental setup is designed to capture multiple left stance periods and the subsequent right stance periods during a longer walking sequence.

The setup comprises a chair and two Hawkin Dynamics force plates (Hawkin Dynamics LLC, Westbrook, USA) which are placed in a bilateral configuration as shown in Fig. 1. The force plates are placed back-to-back in walking direction with a displacement of 15 cm across the walking direction and levelled to ground, allowing for a natural walking style.

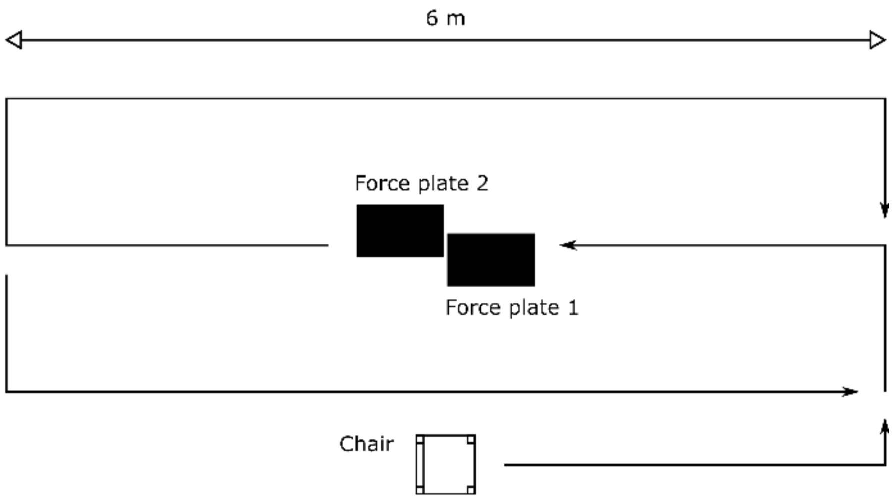

Figure 1: Schematic experimental setup with two force plates and a chair.

Sufficient room has been provided before and after the force plates in order to allow subjects to accelerate and decelerate. When executing the protocol, the subjects walk over the force plates multiple times, always approaching them from the same side. When returning, the subjects alternately take a left or right turn, in order to avoid a circular side bias. The complete sequence is considered as one run and consists of ten walking rounds. In total, three runs are carried out in a trial, interrupted by a pause each (see Sec. 3.4). Fig. 2 shows the laboratory setup.

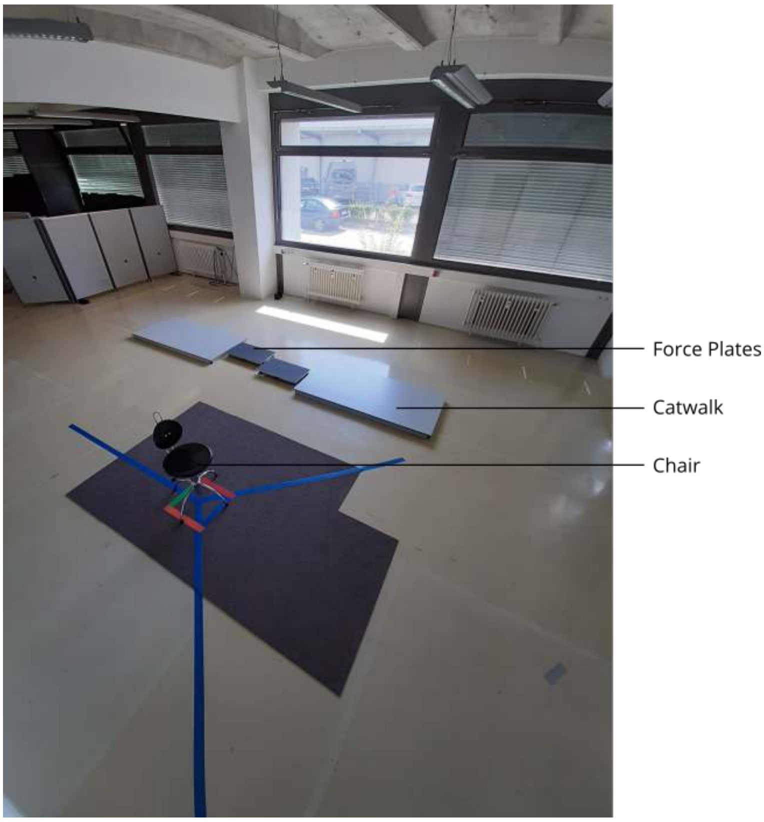

Figure 2: Photo of laboratory setup with two force plates and a chair.

3.2 Calibration Routine and Data Acquisition

As the Moticon OpenGo App allows both calibrated and uncalibrated operation of sensor insoles, each subject's measurement sequence comprises two trials, respectively. In the calibrated trial, a calibration motion sequence (duration: 01:15 min.) carried out by the subject is used to calibrate the pressure sensors to the subject's foot. The calibration motion sequence consists of slow walking, standing still and shifts of the body weight. The calibration function and the related user interface is readily provided by the Moticon OpenGo App as shown in Fig. 3. In the uncalibrated sequence, no additional action is required. The results are computed for two operation modes separately: uncalibrated and calibrated.

The sensor insole data is recorded at 100 Hz sample rate, with "Full" channel setup selected in the Moticon OpenGo App (including total force, center of pressure, 16 pressure sensors, 3-axis acceleration, and 3-axis angular rate). The force plates capture data at 1000 Hz sample rate. Each protocol trial is preceded by a calibration/validation routine of the force plates, where a calibrated weight (10 kg) is put multiple times on each of the two force plates (center location and each of the four corners). It is validated that the measured force is within 1 % of the calibrated weight (using local gravity). Simultaneously, each run was video taped at 60 fps with a Samsung Galaxy A51 phone camera. Sensor insole data, force plate data and videos were synchronized using the *OpenGo Software* and its data and video import features for visual cross checks of automatic data labeling and post processing results (Fig. 4).

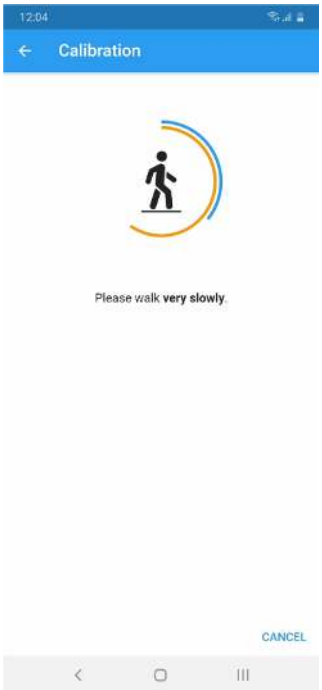

Figure 3: Screenshot of the app user interface guiding through the calibration routine.

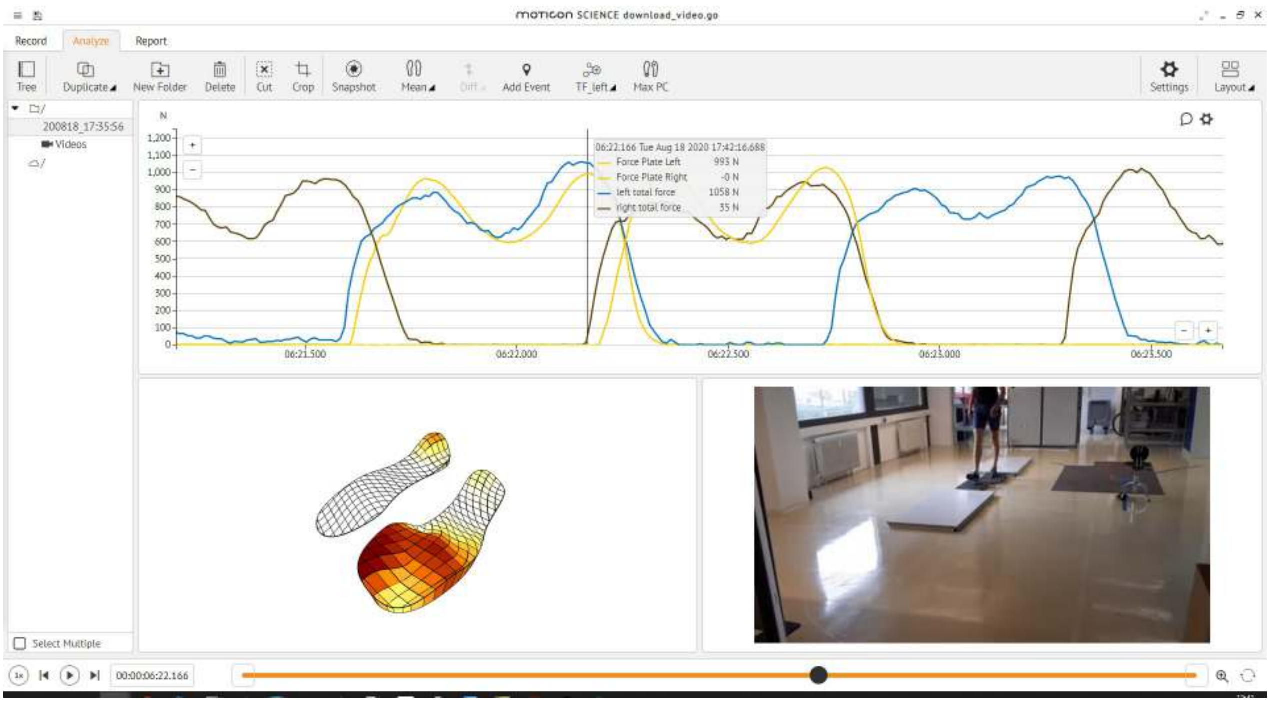

Figure 4: Screenshot of *OpenGo Software* used for synchronizing and labeling data.

3.3 Conditions

In both the calibrated and the uncalibrated sequence, the study protocol defines that each measurement is started with cold sensor insoles (room temperature, approx. 24°C). Intermediate pause periods (2 min. each) let the measurement cover the warm-up phase of the sensor insoles. The motivation behind this protocol is to assess the *OpenGo Sensor Insole* performance in realistic, unsupervised scenarios in home applications or in the field where no warming up in the shoe might be possible.

To further avoid an overly controlled in-lab setup, no manual zeroing is carried out, solely relying on the automatic zeroing performed by the sensor insoles. The automatic zeroing accounts for pressure sensor signal drifts caused by temperature changes in the shoe. An upward raise of temperature causes a simultaneous raise of pressure sensor signals, which results in a bias of the total force values unless continuously controlled. Moticon's automatic zeroing works based on a combined motion and force pattern recognition algorithm. In effect, the feature continuously levels out the raise or drop of pressure sensor signals caused by temperature changes, which is normally performed in a manual process. In the present work, it is investigated how well this feature works in reality (Sec. 5).

In order to eliminate potential effects of different foot wear, all subjects wear the same shoe model (Adidas VRX LOW, article number DB3176) in appropriate size (Fig. 5).

Figure 5: Adidas VRX shoe used in the study for all subjects.

3.4 Protocol

The protocol executed by each subject is as follows:

1. The pair of sensor insoles is kept at ambient room temperature for at least 30 minutes.
2. The protocol starts with the subject sitting on the chair.
3. The sensor insoles are put into the subject's shoe.
4. The measurement is started (on sensor insoles and force plate), subject not yet stepped into the shoes.
5. The subject puts on the shoes.
6. Within 30 seconds after starting the measurement, the subject gets up and starts walking over the force plates.
7. The subjects walks over the force plates 10 times.
8. After the force plates have been crossed 10 times, the subject sits down on the chair and waits for 2 minutes.
9. The walking procedure is repeated 3 times in total (separated by 2 minute pauses sitting on the chair), such that 30 double steps have been carried out on the force plates (60 single-side steps in total).
10. The measurement is stopped after the subject sat down after the last walk.

The entire sequence takes about 10 minutes, roughly covering the typical warm-up phase of the sensor insoles.

After the first protocol execution, the sensor insoles are calibrated for the corresponding subject, following the calibration procedure as guided by the Moticon OpenGo App. This causes calibration data to be stored on the sensor insoles for all subsequent use. When the calibration is complete, the subject takes off the shoes and the sensor insoles cool down to room temperature for at least 15 minutes.

Finally, a second execution of the above protocol steps (1.) to (10.) is carried out, in order to obtain measurement data for the calibrated operation mode.

3.5 Subjects

The study is carried out with $n = 10$ healthy subjects, identified by `ID001` to `ID010` in the results.

The subjects, 4 female and 6 male, are characterized as shown in Table 1 (insole size range equivalent to EU 36/37 to EU 44/45).

	Mean	Min	Max	Std.
Age (years)	33.4	20	41	7.68
Weight (kg)	76.7	56	100	13.8
Insole size (Moticon)	5.2	3	7	1.54

Table 1: Subject details.

4 Data Analysis

This section describes the procedure for quantifying the error of total force measurements.

4.1 Prior Work

In the relevant literature, a repeatedly followed approach is to detect per-step peak forces in both the measurement systen under test and the gold standard measurement system. Comparing the two peak forces, and averaging the results over all steps, then results in an overall error measure.

While per-step peak forces are often of interest and their evaluation is per-se useful, we intend to go beyond peak forces for several reasons:

– Many motion types are not step-centric. The validation of only walking peak forces does not validate the measurement system for other motions.
– Even for walking, we are interested in the entire gait cycle, not just the sequence at and around the peak force.
– For walking styles with multiple force peaks per stance phase, the approach of comparing peak forces is ambiguous. It may occur that, with two local force peaks per stance phase, the first peak of a measurement system shows a better match with the second force peak of the other measurement system. Then, the mathematical maximum of the force per stance phase may not be a solid basis for comparison.
– Since step and peak detection is often carried out manually, this procedure suggests to hand-select peaks, and limit the per-step evaluation to the middle part of a longer walking sequence. This also takes out spurious sensor signals, transient behavior and mis-calibration effects from the error evaluation, and draws an overly optimistic picture of the total force accuracy.

To overcome the limitations of peak force analysis, the analysis of measurement data can take different directions:

– Extend the analysis from peak forces to further motion-specific measures, e.g. force raise times, time between first and second peak, stance phase duration, etc.
– Extend the analysis in a mathematical (stochastic) sense, e.g. higher moments, value histogram, spectral properties etc.
– Transfer the sensor insole data and/or the force plate data into directly comparable datasets, while maintaining the data characteristics of interest.

In this work, we take the latter approach for two reasons:

– The focus is on total force, and the analysis should be applicable to any kind of motion and assess total force accurracy at whatever point in time.
– With *OpenGo*, motion-specific measures, such as the stance phase duration, are determined by fusing pressure sensor data and IMU data (accelerations and angular rates). Comparing the resulting measures with a gold standard would mix pressure/force aspects with IMU processing, which is not the focus here.

4.2 Challenges in Sequence Matching

We aim at comparing all data samples of the sensor insole with the respective force plate data. The problem in this is with the word "respective". If we had a clear one-to-one relationship between the sensor insole data samples and the force plate data samples, computing error measures would be straight-forward. Hindering data processing aspects are:

- The two measurement systems have different sampling rates (with the force plate typically having a higher sampling rate than the sensor insole).
- The two measurement systems may show a relative time offset, both on large scale (e.g. due to clock offset, typically on the order of seconds) and small scale (the sensors are not sampled simultaneously by a common trigger).
- The clock of one or both measurement systems may drift over time, i.e. run slower or faster than the other. This drift may even change over time.
- One or both measurement systems may show sporadic loss of samples.
- One or both measurement systems may show jitter, i.e. the exact time of individual samples may be slightly off the nominal sampling period.

The following section describes an approach for dealing with this situation.

4.3 Sequence Matching using Dynamic Time Warping (DTW)

Dynamic Time Warping (DTW) is a signal processing approach commonly used in machine learning. It allows for a comparison of two "similar" sequences over time, even if they do not evolve in the exact same temporal manner.

For the present study, we deploy DTW as part of the following data preprocessing:

- Take all sensor insole samples as starting point.
- Make sure that the synchronization with the force plate data is within 0.1 s throughout the measurement.
- Resample one force plate sample per sensor insole sample (sample picking without interpolation), facilitated by the *OpenGo Software* file format (.go).
- Compute a DTW alignment using the "asymmetric" step pattern, with Euclidean distance metric using a Sakoe-Chiba band with window size 10. Given the sampling rate of 100 Hz, this means that the time axis can be "warped" up to 0.1 s.
- Warp the data samples of the sensor insole using DTW-transformed sample indices.

This procedure has a number of desirable properties:

- All challenges described in Sec. 4.2 are solved.
- The general shape of the transformed data is only moderately changed.
- The maximum time warping window of 0.1 s prevents excessive time shifts, which would result in overly optimistic matching of in fact unrelated motion signals of the two measurement systems.

The following Fig. 6 illustrates a sample total force sequence of a sensor insole and force plate, and also shows the warped sensor insole data resulting from the above procedure.

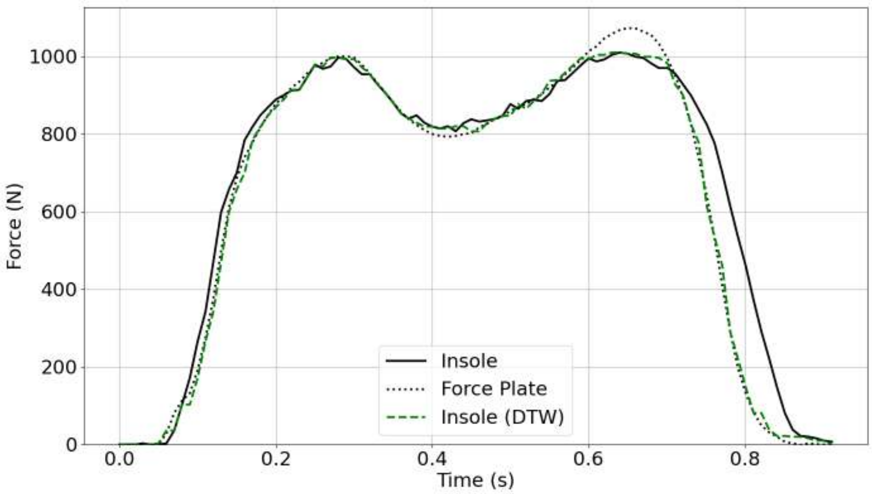

Figure 6: Sample step with DTW sequence matching.

While roughly preserving the original curve shape, we now can directly compare the two measurement systems exempt from synchronization issues.

As a concluding remark, note that this procedure puts exclusive focus on comparing two measurement systems according to amount, not timing. If the task was to evaluate whether a sensor insole measures e.g. total force slopes at the very same point in time as the force plate, then time warping should not be applied. This is, however, not subject of this study.

4.4 Accuracy Measures

Based on original and time-warped sensor insole data, the following total force error measures are calculated to assess accuracy. In this context, "error" always denotes the deviation between the total force measured by the sensor insole, and the total force measured by the force plate (reference, "gold standard").

– Normalized mean absolute error (NMAE): The NMAE normalizes the mean absolute error by the mean of the reference (force plate). This way, the effect of different subject body weights is mitigated. Calculating a mean relative error would not be meaningful since time periods with very low or zero force (e.g. swing phases) would contribute with a huge relative error, dominating the overall result. In order to give the NMAE a direction (positive/negative), we multiply the NMAE with the sign obtained from computing the mean error.
– Peak force: Per step, the difference of the maximum force as obtained from the two measurement systems.
– Error histogram: The error histogram provides an accumulated yet still detailed view on the amount of error across a measurement, showing how the error distributes around the mean.
– Zeroing offset: The residual total force during the swing phases before and after a step on the force plate. We assume no significant pressure during swing phases, and consider any measured load as being due to a zeroing offset.

5 Results

5.1 Overall Results

The overall results for the NMAE and peak error, averaged over all subjects, are summarized in Table 2.

	Uncalibrated	Calibrated
Average NMAE	7.48 % (3.14 %)	0.62 % (3.27 %)
Average peak error	20.2 % (6.11 %)	3.51 % (4.78 %)

Table 2: Overall results (averaged standard deviations in brackets).

Table 3 presents the amount of error in a different way, showing the average absolute values. Certain foot characteristics lead to rather low/high values. In order to provide some intuition for this, Table 3 also provides the averages for measurements where the NMAE/peak error values are below and above zero, respectively. Example: For those calibrated measurements where the peaks are too low, they are on average 3.39 % too low.

	NMAE Uncalibrated	Peak error Uncalibrated	NMAE Calibrated	Peak error Calibrated
. Avg. of all values ≥ 0	7.48 %	20.2 %	2.66 %	10.4 %
Avg. of all values < 0	n/a	n/a	1.41 %	3.39 %
Avg. of all values	7.48 %	20.2 %	2.04 %	6.90 %

Table 3: Average absolute values. Overall, and separated for positive/negative values.

Turning to the zeroing offset, Table 4 shows the average values of all 30 steps, as well as separated for the three runs containing 10 steps each. The average values are computed over all $n = 10$ subjects.

	Zeroing offset Uncalibrated	Zeroing offset Calibrated
Run 1	7.8 N	8.9 N
Run 2	5.2 N	5.1 N
Run 3	4.4 N	5.1 N
Overall	5.8 N	6.4 N

Table 4: Average zeroing offset. Overall, and separated for the three runs.

As expected, there are no significant differences between uncalibrated and calibrated. A per-step analysis of the zeroing offset is provided in Sec. 5.3

5.2 Results per Subject

Fig. 7 shows the NMAE and peak force error per subject along with the standard deviation (over 30 steps), both for the uncalibrated and calibrated operation mode.

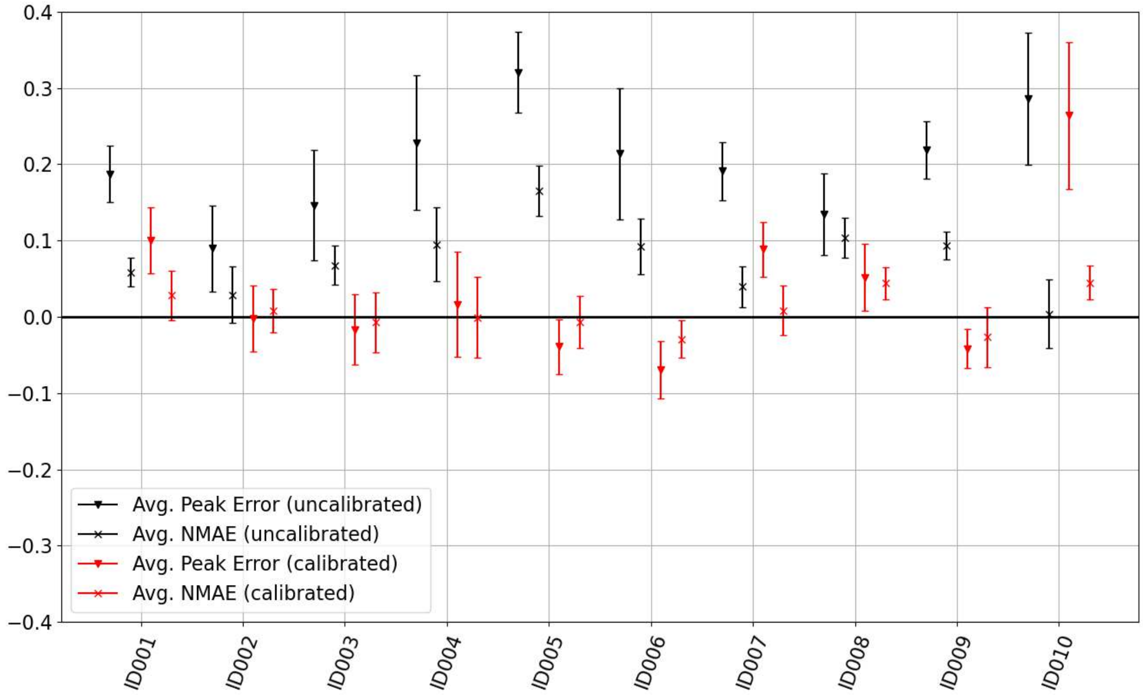

Figure 7: Overall results per subject.

5.3 Results over Time

To analyze the behavior with respect to temperature changes of the sensor insoles, Fig. 8 shows the results for the individual step trials (from step 1 to step 30), averaged over all subjects. This reflects a full warm-up phase. The line gaps indicate the pause times, i.e. steps 11 and 21 are preceeded by an extended warm-up period of 2 minutes.

Fig. 9 shows the average total force zero levels (in Newton) over the step number, both for the calibrated and uncalibrated runs. The step number refers to the 30 force plate steps that were carried out by each subject. The zeroing offset is the residual total force during swing phases, averaged over a time period before and after each force plate step, i.e. 100 ms in total per step.

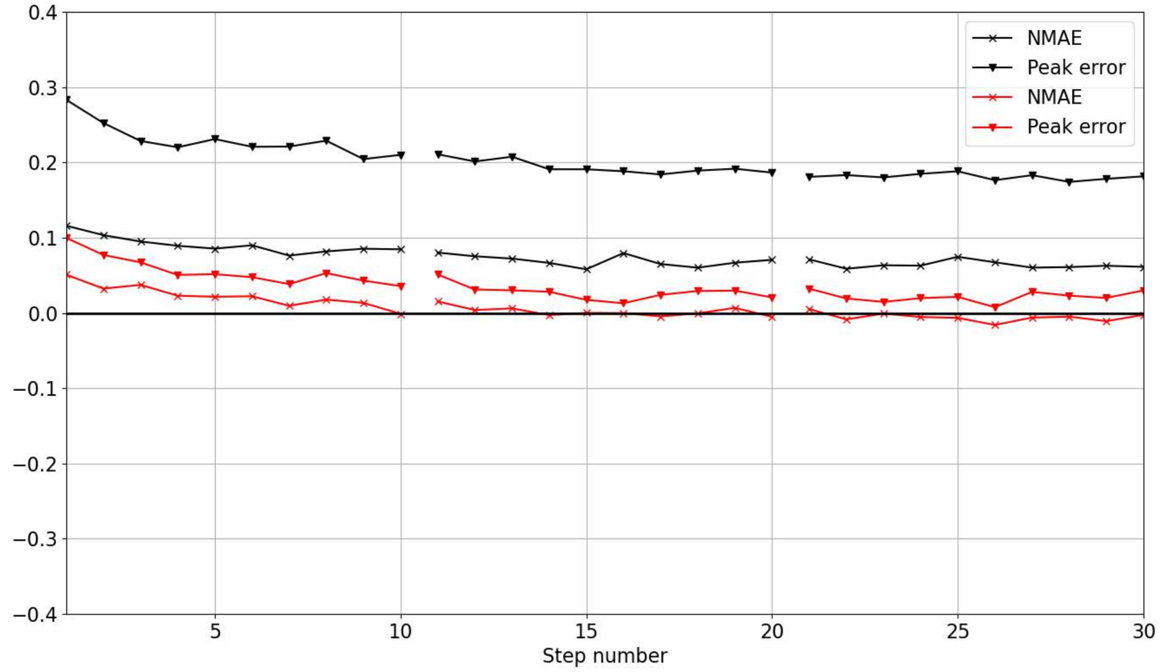

Figure 8: Results over steps carried out on the force plate.

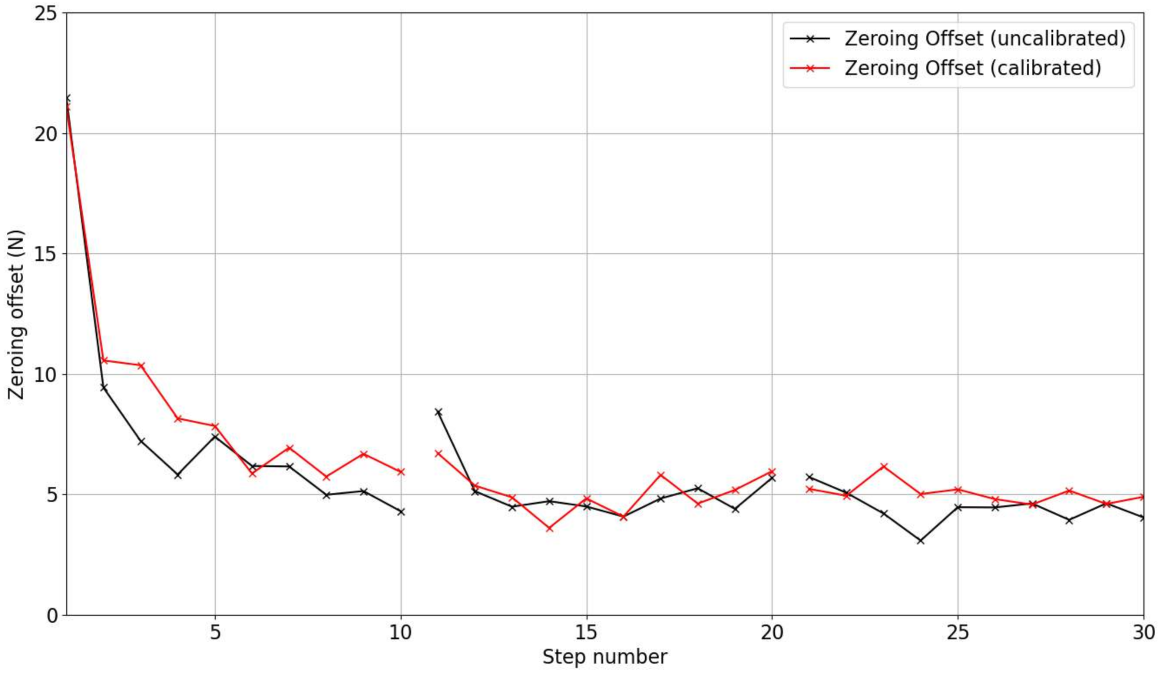

Figure 9: Zeroing offset over step number (average of all $n = 10$ subjects).

5.4 Detailed Results

The appendix shows detailed results per subject:

- The total force averaged over all left/right steps per subject, resulting in a characteristic "average step".
- The error histogram of the total force per subject.

6 Discussion

The best total force accuracy results were obtained in the calibrated runs, where the average NMAE was as low as 2.04 % and the average peak error 6.90 %. In this context, and with respect to in-field and non-supervised use cases, also the results per subject shall be highlighted. The absolute average NMAE was in the range of 1 % to 5 % for five subjects, and < 1 % for the other five subjects. Only one out of ten absolute average peak errors per subject was > 10 % (26.4 %, subject ID010), four values were in the range of 5 % to 10 %, and five values were < 5 %.

For all $n = 10$ subjects, both the average NMAE and the average peak error were lower for the calibrated run compared to the uncalibrated run.

The average NMAE and peak errors over all 30 steps (Fig. 8) show higher yet constantly decreasing values for the first run. This holds for the results of the calibrated trial as well as for the uncalibrated trial. In run two, the values only decrease slightly, and remain almost constant in run three. The reason for this behavior is that the automatic zeroing feature further improves the total force accuracy as the step count progresses. It starts from a high level of precision for the total force errors after just a few steps (≤ 10 %), and brings down the average error rates below 5 % in run two and three.

Fig. 9 agrees with these findings as it shows higher zeroing offsets for the first few steps, and converges to approx. 5 N from step five onwards. This very low level of residual load is considered close to optimal, in particular since it is partly due to sensor signal noise.

Summarizing the outcomes, this study has shown that the *OpenGo Sensor Insole* (model: insole3) is capable of reaching a level of total force accuracy meeting highest standards of scientific research in sports science and clinical studies. However, the results were obtained from normal walking motion only, and it has to be shown in further research that high standards of accuracy can also be achieved for running, jumping, and static situations.

A Appendix

Subject ID001

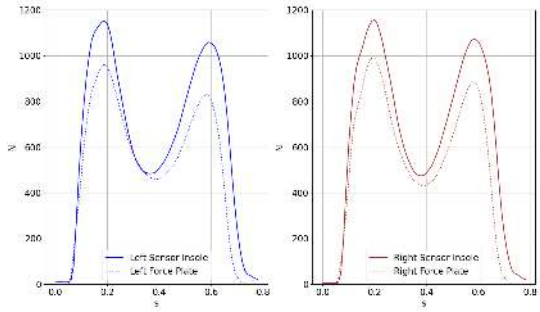

Figure 10: Average step, uncalibrated

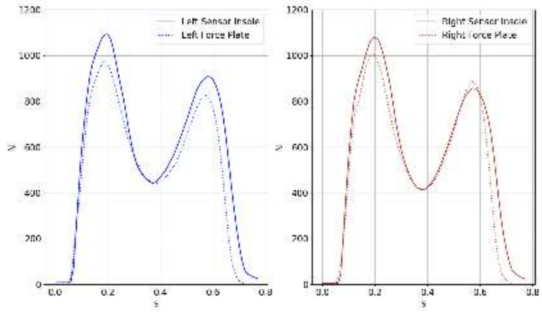

Figure 11: Average step, calibrated

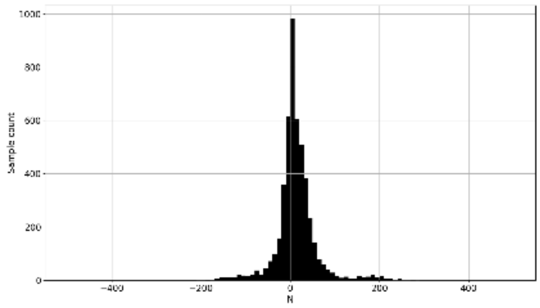

Figure 12: Error histogram, uncalibrated

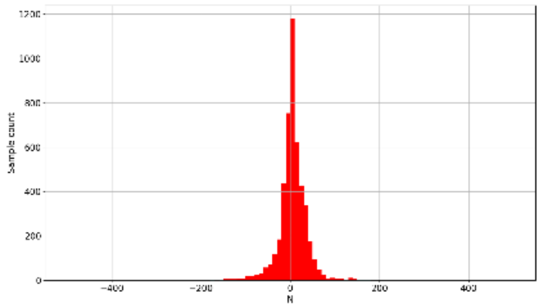

Figure 13: Error histogram, calibrated

Subject ID002

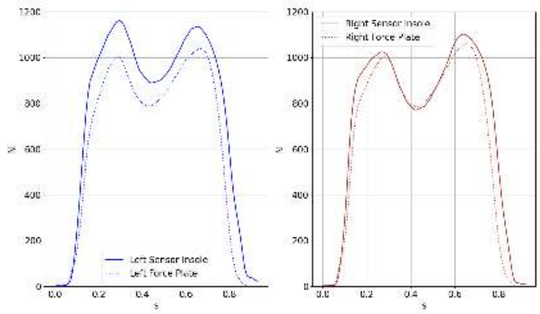

Figure 14: Average step, uncalibrated

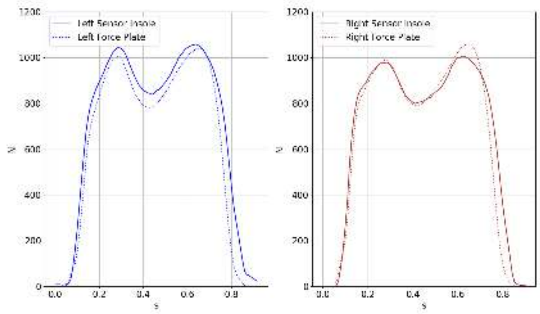

Figure 15: Average step, calibrated

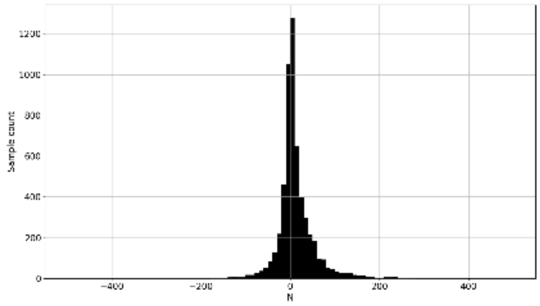

Figure 16: Error histogram, uncalibrated

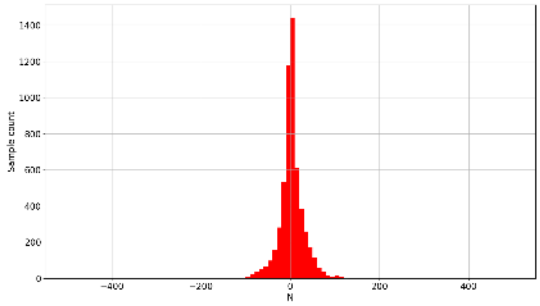

Figure 17: Error histogram, calibrated

Subject ID003

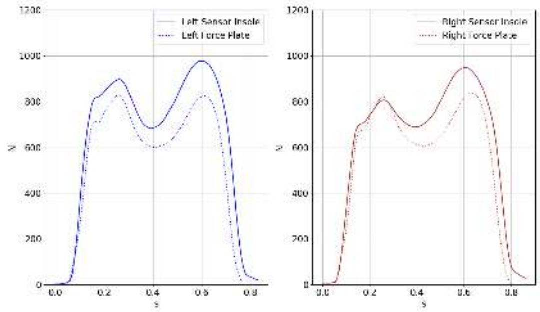

Figure 18: Average step, uncalibrated

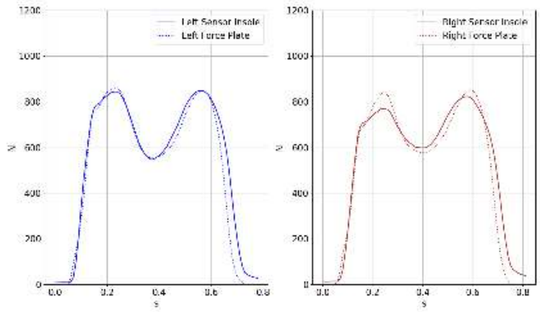

Figure 19: Average step, calibrated

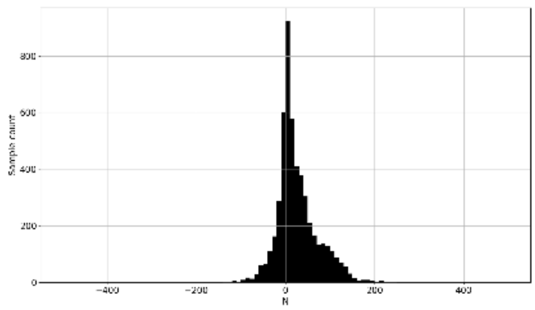

Figure 20: Error histogram, uncalibrated

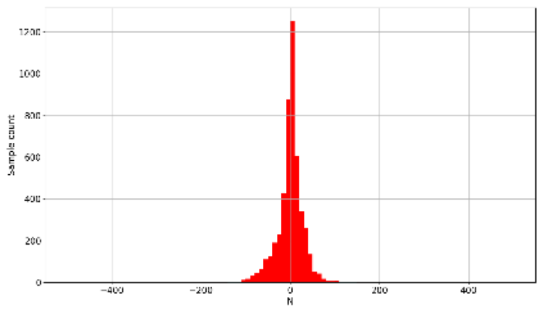

Figure 21: Error histogram, calibrated

Subject ID004

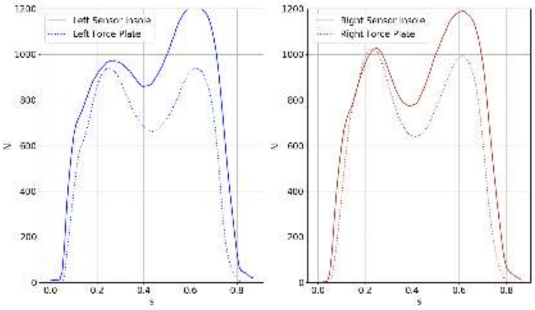

Figure 22: Average step, uncalibrated

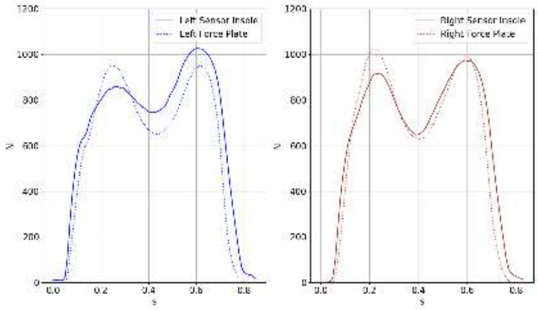

Figure 23: Average step, calibrated

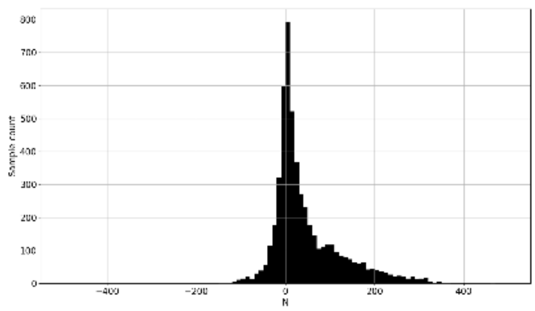

Figure 24: Error histogram, uncalibrated

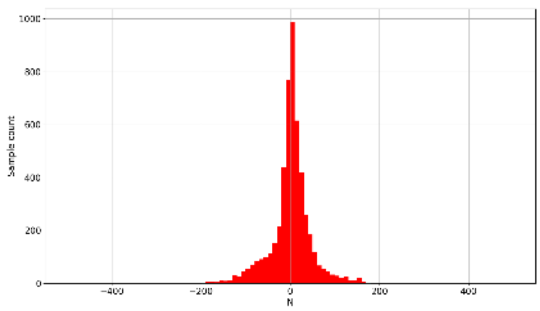

Figure 25: Error histogram, calibrated

Subject ID005

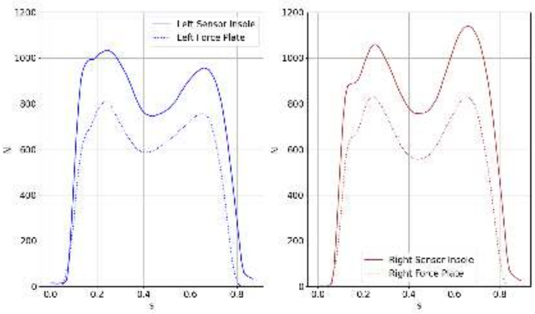

Figure 26: Average step, uncalibrated

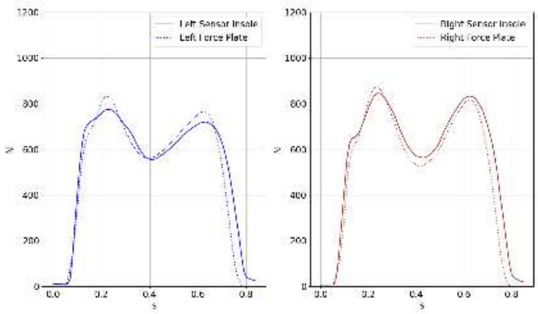

Figure 27: Average step, calibrated

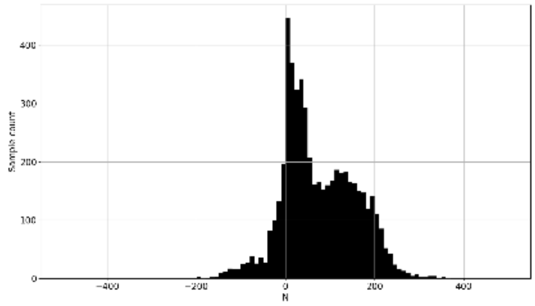

Figure 28: Error histogram, uncalibrated

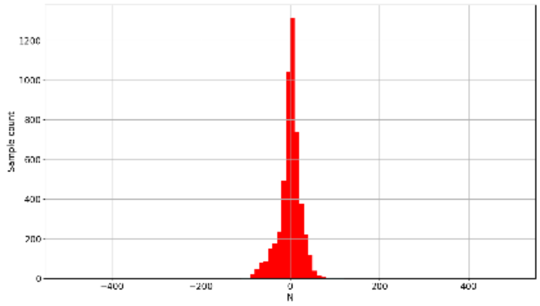

Figure 29: Error histogram, calibrated

Subject ID006

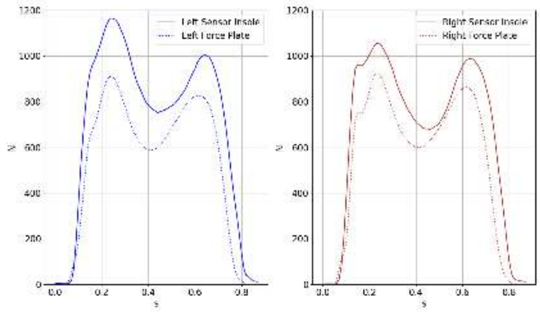

Figure 30: Average step, uncalibrated

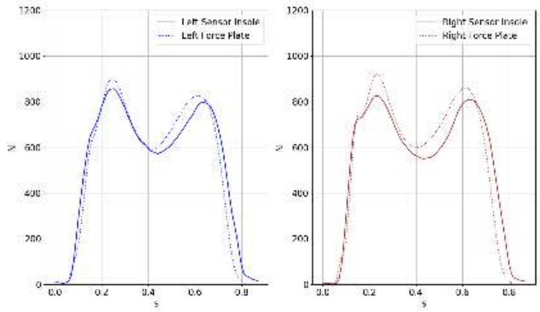

Figure 31: Average step, calibrated

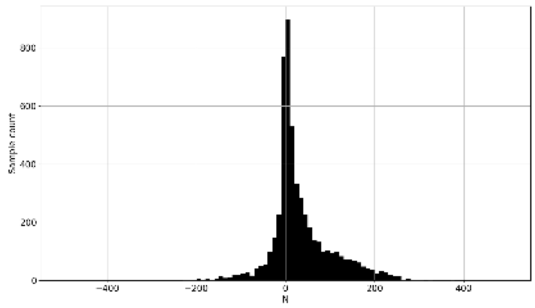

Figure 32: Error histogram, uncalibrated

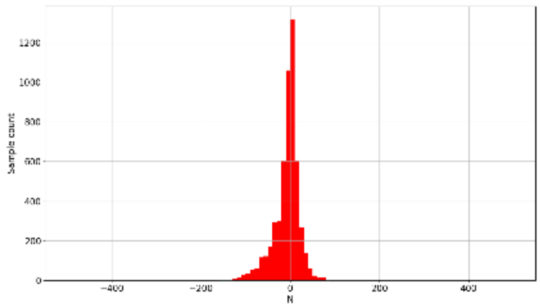

Figure 33: Error histogram, calibrated

Subject ID007

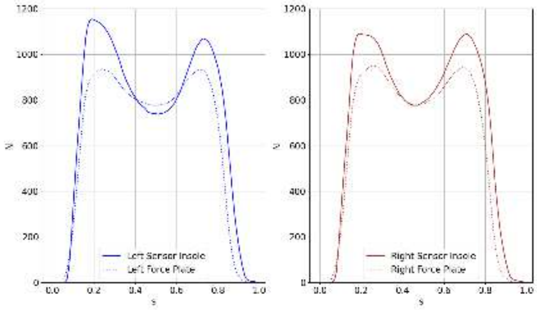

Figure 34: Average step, uncalibrated

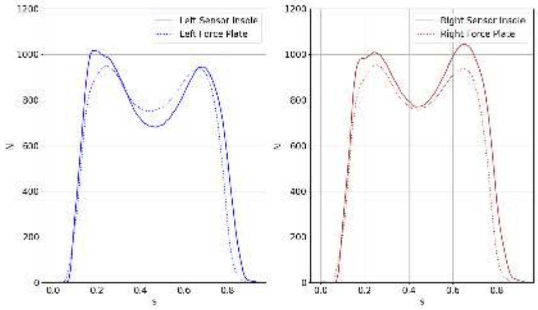

Figure 35: Average step, calibrated

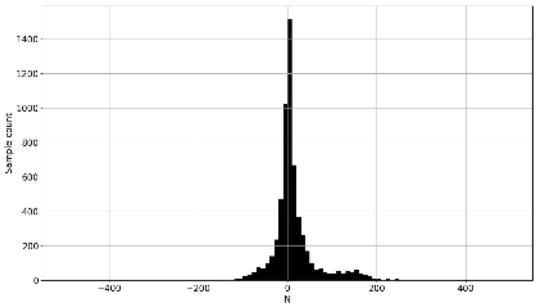

Figure 36: Error histogram, uncalibrated

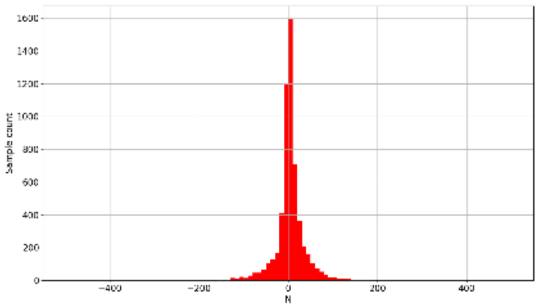

Figure 37: Error histogram, calibrated

Subject ID008

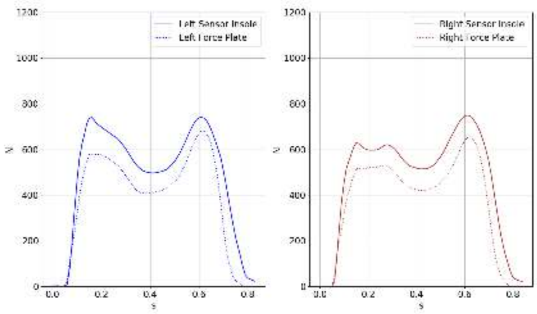

Figure 38: Average step, uncalibrated

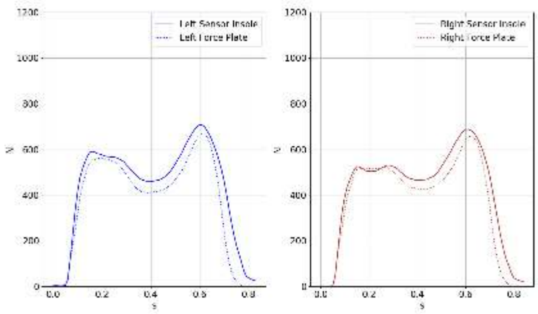

Figure 39: Average step, calibrated

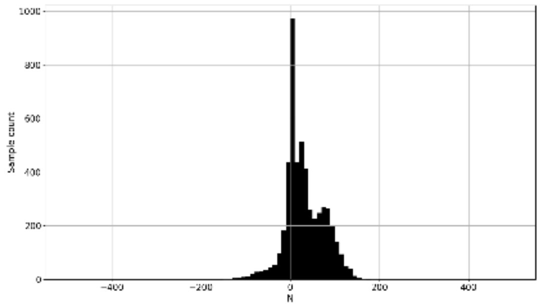

Figure 40: Error histogram, uncalibrated

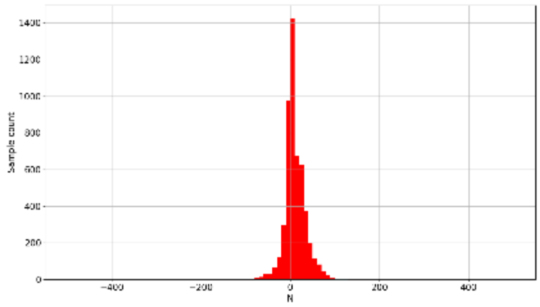

Figure 41: Error histogram, calibrated

Subject ID009

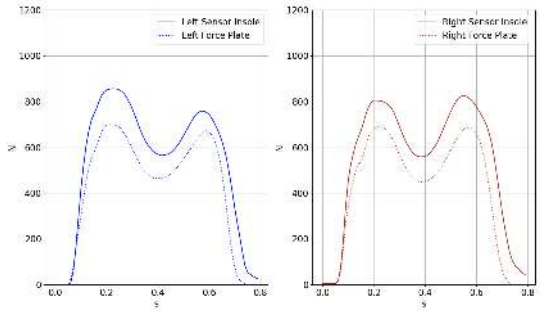

Figure 42: Average step, uncalibrated

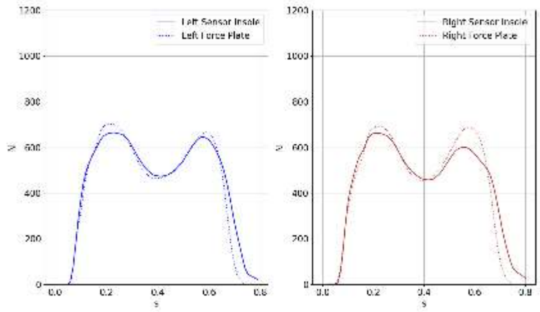

Figure 43: Average step, calibrated

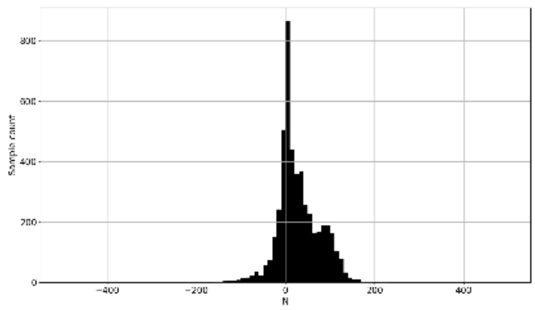

Figure 44: Error histogram, uncalibrated

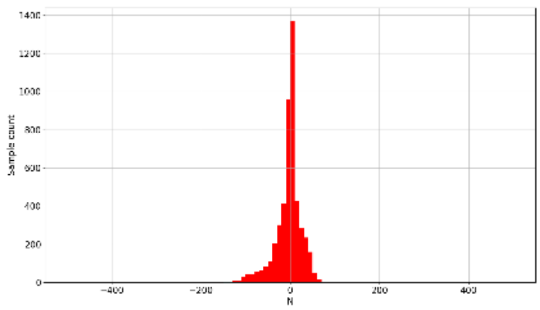

Figure 45: Error histogram, calibrated

Subject ID010

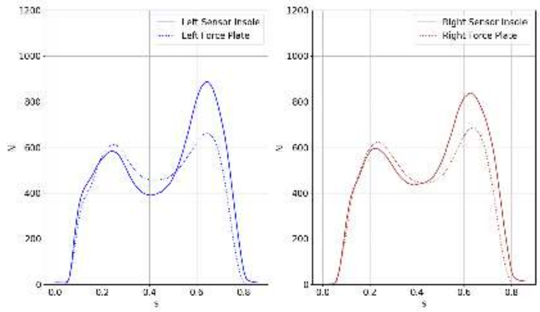

Figure 46: Average step, uncalibrated

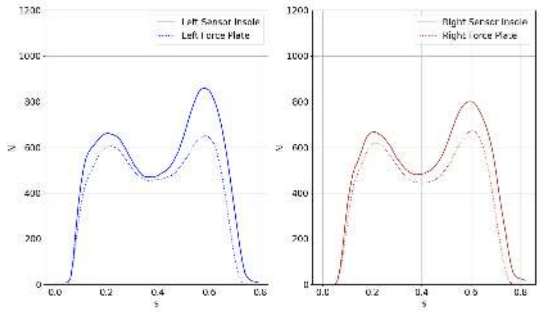

Figure 47: Average step, calibrated

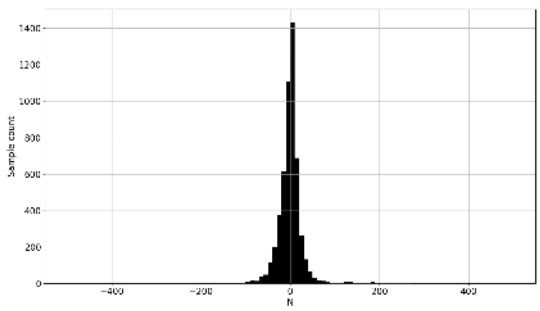

Figure 48: Error histogram, uncalibrated

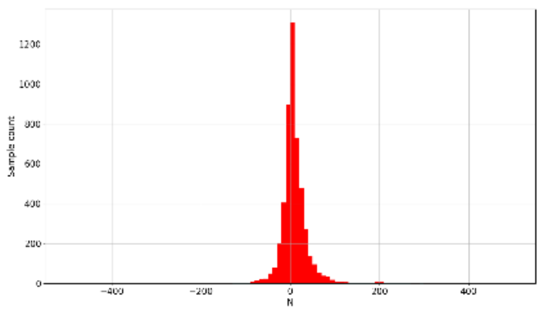

Figure 49: Error histogram, calibrated