# INSTRUMENTATION TO MEASURE CONTACT FORCES IN CLIMBING

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## Abstract

The measurement of contact forces between the climber and the wall is important to investigate climbing movements and asses skills. To this end, several instrumented climbing holds have been proposed. However, either these instrumentations are restricted to force measurements in one or two dimensions, or they are so expensive that no full instrumentation of a climbing wall has been reported so far. Here, we describe the design of a novel instrumentation that can measure forces in all three dimensions, with a focus on affordability. Preliminary validation results show that the worst root mean square error occurs perpendicular to the wall (3.7% of the maximum tolerable axis load of 1 kN) whereas the maximum error occurs in the plane of the wall (9.2% of the maximum tolerable axis load of 1 kN horizontally in plane of the wall). A more precise modelling of the sensor mechanics may provide a further increase of sensor accuracy and reduce crosstalk, even for multi-axial load cases.

**Keywords:** fully instrumented climbing wall, weighing cells, measurement error, low-cost sensor,

# TITLE OF ABSTRACT IN FRENCH

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## Abstract

200 words max in French

**Keywords:** 3-5 keywords not part of the title in French

## Introduction

The measurement of contact forces between the climber and the wall is important to investigate climbing movements and to asses skills. Therefore, it has been frequently proposed (e.g. by Amca, Vigouroux, Aritan, & Berton, 2012; Vigouroux, Quaine, Labarre-Vila, & Moutet, 2006) to measure such forces, in addition to established methods like anthropometric measures, oxygen uptake and handgrip dynamometry (Baláš, 2016; Giles & Brandenburg, 2016). So far, contact forces have been measured either by uniaxial-instrumented setups requiring a distinctive loading direction or by an expensive multiaxial-instrumentation of up to four handholds (studies summarized by Fuss & Wolf, 2016). Only once eight holds of a climbing route were instrumented (Fuss & Niegl, 2008). Therefore the analysis of contact forces in all three dimensions is currently limited to short boulder problems and does not allow analysis of typical climbing routes. Hence, there is a need for cost-effective sensors to establish a fully-instrumented climbing wall with typical climbing holds. Our group demonstrated that a uniaxial force sensor in the case of a single distinct loading direction could contribute to a performance analysis in climbing (Bauer, Simnacher, Stöcker, Riener, & Wolf, 2014). In order to avoid the need for proper alignment and allow the measurement of grips with changing load direction, we developed a 2 Degrees of Freedom (DoF) instrumentation based on two parallel arrangements of commercially available weighing cells. The instrumentation was not perceivable during climbing and could easily be mounted to the backside of climbing walls with insets (otherwise, 120 mm in diameter hole required). Acceptable measurement characteristics were achieved while hardware costs were at about CHF 300. Thus, contact forces with a distinctive loading direction within the plane of the climbing wall, e.g. at crimps, can be monitored in an affordable manner (Bauer et al., 2014). To enable monitoring of contact forces in all three dimensions, this paper presents a further development of our 2 DoF instrumentation. We decided to stick to affordable, commercially available weighing cells in order to reduce the manufacturing and calibration effort associated with the placement of strain gauges. As we are currently interested only in the contact force-time curves at all hand/foot holds of a boulder, we decided to ignore moments introduced at the holds (which can, for instance, in some cases allow the localization of the centre of pressure on the hold). Thus, a 3 DoF instead of a 6 DoF instrumentation was developed.

## Material and Methods

Four weighing cells (3135_0 Micro Load Cell CZL635, Phidgets Inc., Canada) were combined to measure contact forces in the direction of gravity (assuming the wall is not inclined). The parallel arrangement was necessary to cover expected maximal loads, i.e. the range of the single weighing cell of 500 N was quadrupled. Additional weighing cells of the same type were incorporated to enable monitoring of contact forces in all spatial dimensions. However, as contact forces perpendicular to the direction of gravity were expected to be lower, only two weighing cells were combined for the remaining axes (see Figure 1). Each set of weighing cells was connected to one bridge input of the amplification unit (1046 0, Phidgets Inc., Canada). The amplification unit contained a microprocessor, an analogue digital converter and an amplifier, integrated in a single circuit board. Processed sensors’ signals were transmitted to a PC via USB supporting a 24 bit resolution. Our chosen design was a compromise between size of the instrumentation and the minimization of coupling errors, while keeping the overall material costs below CHF 750. The wall fixation unit can be mounted on any flat surface of at least

170 mm in diameter. The hold fixation unit can tolerate a wall thickness between 15 and 20 mm; otherwise, the four beams fixed to the wall fixation unit have to be replaced, which will change the current height of the instrumentation (140mm including amplification unit and cover). The overall weight of the instrumentation without the wall fixation is 0.8 kg, with the fixation it is 4.2 kg.

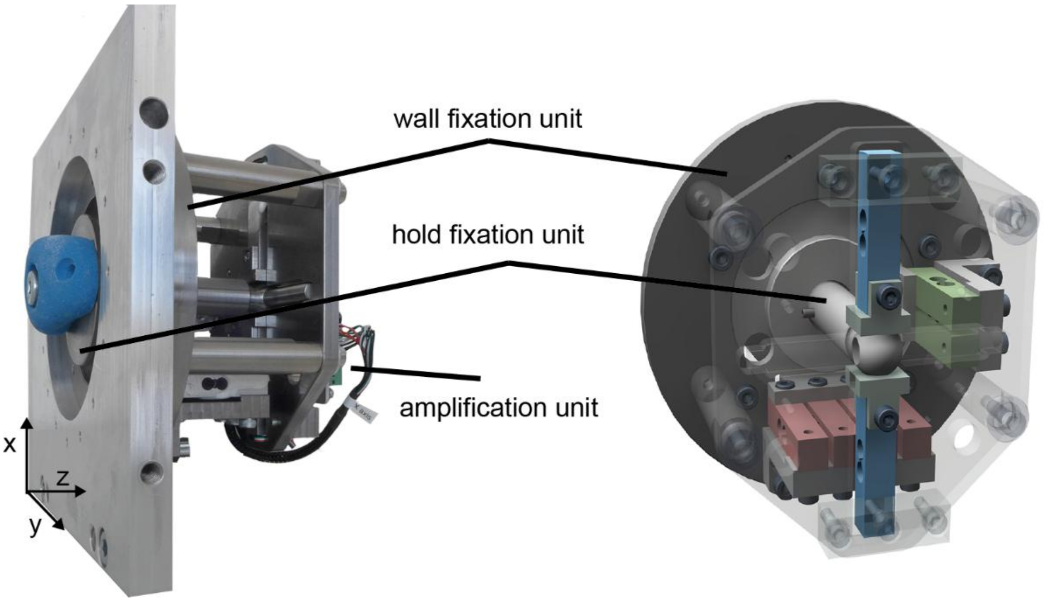

**Figure 1** Our instrumentation to measure contact forces. Left: Photo of the assembled instrumentation. The blue hold can be replaced by any arbitrary hold (the wooden cover disc of the hold fixation unit is not shown here). Right: CAD render of the backside of the assembled instrumentation. Weighing cells are highlighted in red, green, and blue, measuring contact forces in x, y, and z direction, respectively.

To determine the measurement characteristics of our new instrumentation, we connected the amplification unit to a PC on which a python script was executed to sample sensor data at 50 Hz. Reference force data was applied to the hold by a material test machine (Zwick 1456, Ulm, Germany, sampling at 50 Hz). Three load cases were considered: (1) only along the x-axis from -1’000 N to 1’000 N, (2) only along the y-axis from -500 N to 500 N, (3) along the z-axis from -500 N to 500 N. Four consecutive cycles per axis were executed within 7 to 10 min. Data of the sensor and of the material test machine were aligned by observed force peaks. To mitigate jitter, all data was resampled at 100 Hz by linear interpolation. A straightforward way to improve the accuracy of the sensor output is to assume that there exist a number of linear correlations between the different axes, which could be described as

$$\boldsymbol{x}_k \propto \boldsymbol{A}\boldsymbol{y}_k \quad for\ k = 1, \dots, N \tag{1}$$

where $\boldsymbol{x}_k$ is the known reference data and $\boldsymbol{y}_k$ is the sensor data.

A direct linear transformation algorithm was used to determine $\boldsymbol{A}$. As $\boldsymbol{x}_k$ and $\boldsymbol{y}_k$ were extended to homogeneous coordinates, $\boldsymbol{A}$ became a 4x4 transformation matrix, and constant offsets between the data and linear error factors were compensated. The first 75% of the data points of each of the three different load cases were combined to compute a matrix $\boldsymbol{A}$ that minimizes the root-mean square (RMS) error over all three load cases. The remaining 25% were used to evaluate the RMS error and maximum error per axis (see Figure 2).

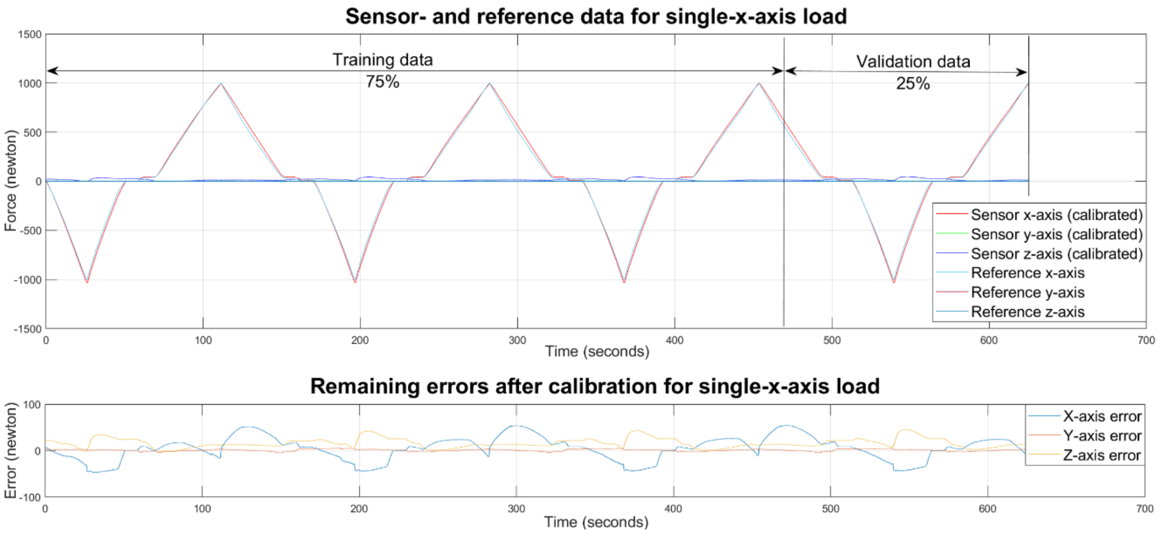

**Figure** 2 Results of exemplary single-axis load case. Top: Calibrated sensor data in relation to reference data. Out of the three single-axis datasets, the first 75% of all samples were used for calibration. The remaining 25% for validation. Bottom: Remaining errors in sensor data after calibration. Errors in y and z demonstrate the crosstalk of the sensor. Note, that the scale of the y-axis in the bottom plot is enlarged to improve readability.

## Results and Outlook

In single axis load conditions, the RMS error was 1.6% in x, 3.6% in y and 3.7% in z, and the maximum error was 3.3% in x, 9.2% in y and 6.4% in z, respectively (relative to maximum allowed loads of 2 kN for x and 1 kN for y and z). We are currently investigating if a detailed model of the instrumentation will further improve the accuracy. In addition, we are going to evaluate cross talk in case of multi axis forces and torques.

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