www.s2is.org
International Journal on Smart Sensing and Intelligent Systems
ISSN 1178-5608

A Climbing Hold With an Integrated Three Dimensional Force Measurement and Wireless Data Acquisition

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Submitted: Nov. 10, 2013 ***Accepted: Dec. 10, 2013*** ***Published: Dec. 23, 2013***

Abstract- A three dimensional force measurement system was integrated in a climbing hold. The force measurement system consisted of three orthogonally mounted platform load cells. Data acquisition and power supply of the load cells was performed by a wireless data acquisition system ViFDAQ. Data was transferred by ViFDAQ to a nearby laptop by a wireless Bluetooth connection.

Measurements were done during a regional climbing competition. The instrumented climbing hold was mounted in one of the climbing routes. The forces the athletes exerted on the climbing hold to reach the top were measured. Force data was analyzed and compared to the actual ranking of the athlete in this competition.

Index terms*:* Instrumented climbing hold, force measurement, rock climbing, integrated climbing hold, climbing efficiency, Hausdorff dimension, wireless data acquisition, ViFDAQ.

I. INTRODUCTION

In recent years rock climbing [1] became more and more popular and the number of active athletes is estimated to be over 30 million, worldwide. This sharp rise is due to a strong development of the climbing equipment (e.g. rope, bolts, sit harness and climbing karabiners) minimizing the risk of injury. Additionally, rock climbing is not practiced any longer only on natural rocks but also in indoor climbing halls which are built in nearly every major city. Nowadays, there are more than 450 indoor climbing halls in Germany, and the number is still increasing. Thus, rock climbing can be done all year long independent of the weather conditions.

A lot of rock climbing competitions ranging from small local competitions to world championships takes place in these indoor climbing halls and rock climbing is on its way to become part of the Olympic Games. At these competitions the climbing athlete is only allowed to use the climbing holds for upwards movement. Rope and securing points are only used for preventing the athletes to fall to the ground. The goal of these competitions is to climb the route to the very last climbing hold.

There are several articles in scientific literature to measure the forces a climber is exerting on a climbing hold in order to reach the top of a climbing route. The first measurement was done by Rougier [2] in 1995. Testa [3] installed a three dimensional force sensor in a climbing hold and similar measurements were done by Quaine [4] who additionally recorded the ascent on video tape. Fuss [5] describes a climbing wall equipped with eight climbing holds to measure forces and moments exerted on the hold. Another climbing wall equipped with a six-dimensional force-moment-measuring system is described by Aladdin [6].

Thus, a multidimensional force measurement is state of the art and different measurement systems are used and corresponding sensors are commercially available. Piezoelectric sensors are based on the physical principle that electrons are released by a quartz under pressure. This charge is correlated to the affecting force. The main advantage of the piezoelectric sensors is their very short response time. However, compared to strain gauges they have a limited sensitivity. Strain gauges are measuring the change in electrical resistance due to a deformation. Using a Wheatstone bridge arrangement influence of temperature and lateral loading can be compensated.

If strain gauges are mounted on an arbitrary shaped object extensive calibration has to be done. Thus, force measurement is usually done using platform load cells on which strain gauges are mounted. Platform load cells are blocks of metals which are optimized that lateral forces are eliminated, temperature effects are compensated and the response signal is linear to the load applied to the cell.

At the climbing hold described in this work three platform load cells are installed vertically to each other. Each of these load cells is measuring one of the three components of the force. Moments are not measured.

However, all force measurement systems described in scientific literature are cable based [7][8]. Thus, there is a cable for power supply, excitation voltage and for data acquisition to each sensor resulting in a laborious effort for installing the sensors. Additionally, these cables can be damaged very easily during normal operation of a climbing hall or during a competition.

That's why the instrumented climbing hold was equipped with the wireless data acquisition system ViFDAQ [9]. This data acquisition system is able to supply the platform load cells with the necessary excitation voltage, amplifies and processes the signals and transmits them via Bluetooth to a nearby laptop. The instrumented climbing hold can be installed on the climbing hall within some minutes and can be operated due to an integrated accumulator for several hours.

Extensive measurements were done during a local climbing competition. The forces of the different climbers were measured, climbing efficiency was calculated by using different algorithms proposed by Fuss [5]. This analysis was compared to the results of the competition.

II. MATERIALS

The hardware consisted of a force measurement unit, a fiber glass coverage with the climbing hold and the data acquisition unit.

a.) Force measurement unit

The force measurement was done using three orthogonally mounted platform load cells, type HCLA, manufactured by HBM (Figure 1). The measurement range of these cells was 2500 N with a responsitivity of 2 mV/V.

In order to prevent any damage of the equipment and any risk of injury to the athletes, the load cells were covered by a coverage made of glass fiber. On top of this coverage the climbing hold is mounted (Figure 2).

Figure 1 Orthogonally mounted load cells.

Figure 2 Integrated climbing hold.

b.) Data acquisition system - ViFDAQ

Data was acquired by the miniaturized and wireless data acquisition system ViFDAQ (Figure 3) which is described in detail in [9] and came into operation at numerous measurement tasks [10]. The dimensions of ViFDAQ are 20 mm x 30 mm x 15 and it was installed behind the fiber glass coverage. ViFDAQ provided the excitation voltage of the load cells of 5 V. The signal of the load cells was amplified by a factor of 100. Data was sent for further processing to a nearby laptop via the Bluetooth protocol. The data acquisition rate was 50 Hz.

c.) Climbing wall

The instrumented climbing hold was installed on an artificial climbing wall. The wall was slightly overhanging with an inclination of 9°. The set-up of the climbing holds of the climbing route is shown in Figure 4. The climber started with both hands at the first hold and had to grasp the second hold which was the instrumented climbing hold where the force measurement took place.

The hold was fitted in a way that the competitors had to climb the complete sequence in a compelling order:

a. First, the participants had to do an unconsciously static standard movement on the specific hold.
b. Preparation phase – correct feed positioning and taking place to the starting position for the add-on movement.
c. Main phase – entire shift of the body centre of gravity until the possible highest point along the climbing wall just for catching the next hold.

d. Final phase – repositioning of the feet and retaking the stable position that the climber could reach the third hold with the right hand to get the fourth hold with the left hand to continue to the top.

The measurement took place during a local climbing competition. Twenty one athletes participated on these measurements. They were divided into two groups: sixteen climbers were less experienced climbers and competed in the "Hobby" class of this competition. The remaining climbers were much more experienced and competed in the professional class of this competition. One goal of this study was to investigate if these two groups, the less experienced climbers of the "Hobby" class and the more advanced climbers could be distinguished by their way of climbing.

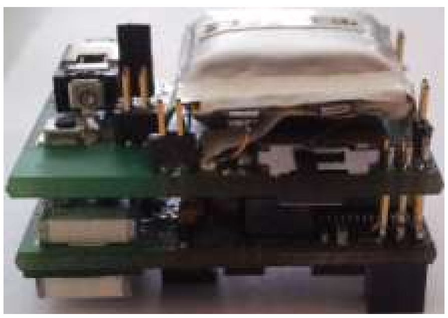

Figure 3 Miniaturized data acquisition system "ViFDAQ".

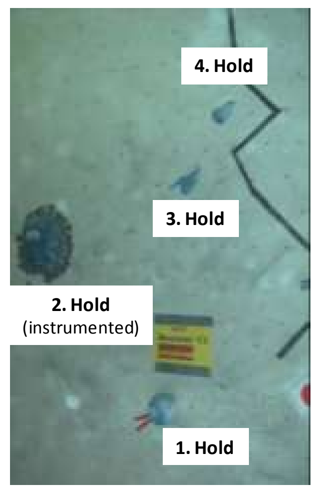

Figure 4 Climbing wall with instrumented climbing hold.

The list of contestants is given in Table 1. Each athlete can be identified by the unique ID. In the second column of Table 1 the class is given in which the climber competed. The third column indicates the sex of the climbers. Most important, the fourth column gives the rank of the climber in this competition. Climber 506 won the Hobby class while climber 508 finished at the thirtieth place. Contestants 598 and 599 were climbers of professional level but did not compete in this competition and were not ranked.

The climbing route shown in Figure 4 was a fairly easy one. Nearly every climber succeeded to climb it on the first try. Only climber 508 needed two tries. The first one is given as 508-1 in Table 1, the second try as 508-2.

Table 1 List of contestants

ID	Class	Sex	Ranking	ID	Class	Sex	Ranking
506	Hobby	male	1	515	Hobby	female	28
505	Hobby	male	2	508-1	Hobby	female	30
512	Hobby	male	3	508-2	Hobby	female	30
504	Hobby	male	6	223	Profi	male	8
513	Hobby	male	7	211	Profi	male	12
519	Hobby	male	8	210	Profi	male	16
507	Hobby	male	9	202	Profi	male	18
509	Hobby	male	10	103	Profi	female	2
526	Hobby	female	11	598	Profi	male	---
511	Hobby	male	19	599	Profi	male	---
525	Hobby	male	21				

III. Methods

Up to now there are no objective criteria to indicate the difficulty of a climbing route. The standard procedure for grading a climbing route consists in that every climber having climbed the route expresses his subjective grading and after extensive discussion a commonly accepted grading is found.

Each climber climbs according to his technical skills, force and size. So it is very difficult to judge whether an ascent was done efficiently or not. Nevertheless, Fuss [5] tried to establish some criteria describing the climbing efficiency.

i.) Time of contact: The longer a climber has to hold a climbing hold, the more the muscles get tired. So, a fast ascent may signify an efficient climbing style.

ii.) Force: The higher the force a climber is exerting on the hold, the sooner the muscles grow tired. A small force indicates a good climbing style.

iii.) Relation of vertical force to normal force: The applied force can be projected on a three dimensional orthogonal coordinate system. The vertical force, the force normal to the surface of the climbing wall and the lateral force which is perpendicular to the vertical and normal component and parallel to the surface of the climbing wall (see Figure 5).

Usually, a climber tries to get his center of mass as close to the wall as possible to reduce the normal force and prevent slipping off the hold. So, a high relation of vertical force to normal force may be a result of an efficient climbing style.

iv.) Smoothness: An efficient climber charges the hold smoothly. He just gets hold of the climbing hold and moves steadily on towards the next hold.

v.) Hausdorffdimension: The Hausdorffdimension D calculates the entropy of a signal and is a good summary of the above mentioned criteria for describing an efficient climbing style. The Hausdorffdimension increases with time of contact, applied force and decreases with the smoothness of the applied force. It is defined as (Equation 1)

$$D = -\lim_{R \to 0} \frac{Log\,N(R)}{Log\,R} \qquad \text{Equation 1}$$

N ist the number of boxes of size R to cover a graph completely. In this work the Hausdorffdimension was calculated using the Boxcounting method.

A horizontally or vertically straight line gets a Hausdorffdimension of one. This is a minimum value.

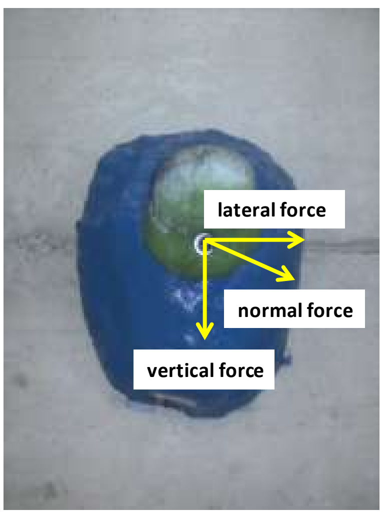

Figure 5 Definition of the vertical, normal and lateral force.

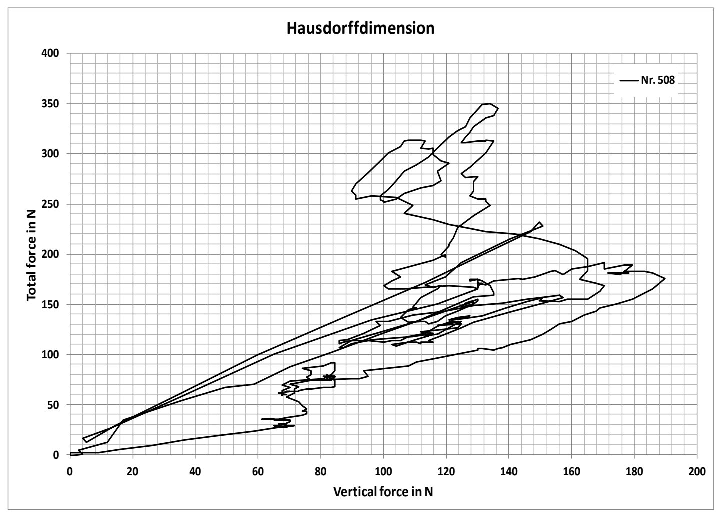

Figure 6 Total force over the vertical force for climber Nr. 508.

The calculation of the Hausdorffdimension was done on a two dimensional scatterplot. The vertical force a climber exerted on the hold is plotted on the abscissa, the total force on the ordinate. The total force over the vertical force of climber Nr. 508 is given in Figure 6. The Boxcounting algorithm is used to count the minimum number of N squares of size R to completely cover the graph of Figure 6.

IV. RESULTS

a. Force Measurements

In Figure 7 the total force of climber Nr.506, the winner of the contest, and climber Nr. 508 who reached the thirtieth place are shown. Climber Nr. 506 held the hold for 7.8 seconds, climber Nr. 508 only for 5.1 seconds. However, climber Nr. 508 did not succeed in climbing the route but fell off.

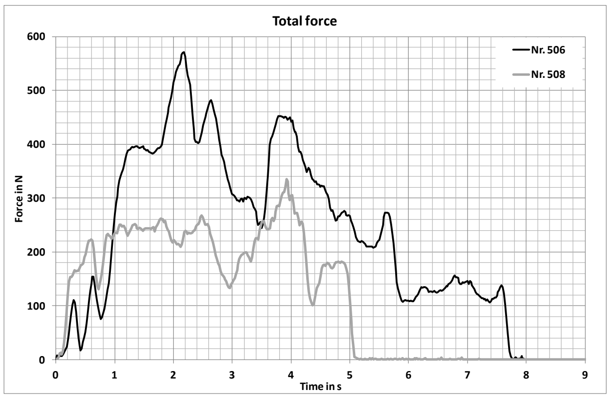

Figure 7 Total force of climber Nr. 506 and climber Nr. 508 exerted on the instrumented climbing hold.

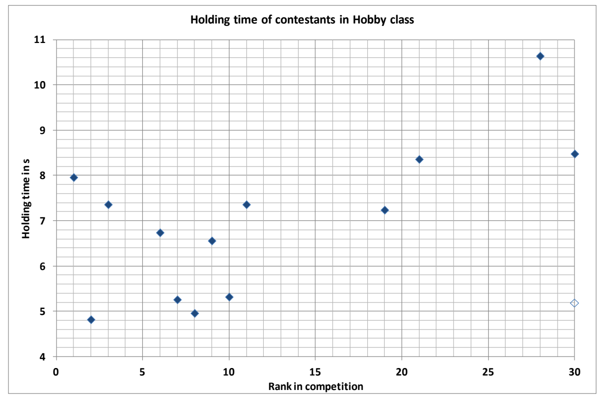

Figure 8 Holding time of contestants of the Hobby class.

It can be seen in Figure 7 that the graph of climber Nr. 506 is much smoother than the graph of climber Nr. 508. This confirms assumption iv.) in chapter III, that the climbing efficiency decreases with the smoothness of the graph.

Climber Nr. 506 used a lot of power – more than 580 N – to climb this route while climber Nr. 508 only exerted 310 N to the climbing hold. Climber Nr. 508 fell off the hold while exerting a force of 180 N to the hold. This indicates that climber Nr. 508 did not fell off due to a lack of power as she was able to hold 310 N just a few seconds before.

b. Holding Time

The time span a climber exerts a force on the instrumented climbing hold in relation to the rank in the competition is shown in Figure 8. It took the climbers between five and eleven seconds. The holding time decreases from the first to the eighth rank in the competition and increases afterwards. This is due to the fact that this climbing move was well inside the limits of the good climbers so there was no need for them to hurry up. On the other hand, for the climbers ranked on the twentieth place and beyond, due to their limited force it took a long time to find a stable position to reach for the next hold. So the holding time of these athletes increased.

c. Hausdorffdimension

The Hausdorffdimension compromises all of the in Chapter III. mentioned criteria for evaluating the climbing efficiency as it increases with holding time, force and decreases with smoothness. The Hausdorffdimension of the two dimensional graph of the vertical force over total force is shown in Figure 9. It can be seen that the Hausdorffdimension increases with the rank of the climber in the competition. There is a positive dependency of the Hausdorffdimension to the rank at the 90% confidence level.

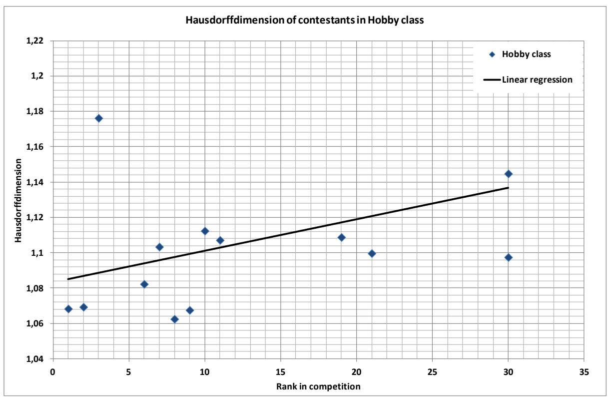

Figure 9 Hausdorffdimension of contestants of the Hobby class.

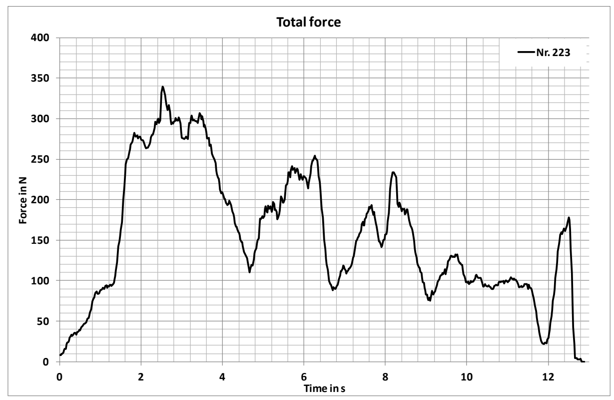

Figure 10 Total force of climber Nr. 223.

d.) Difference Hobby class to Profi class

The Hausdorffdimension of the Professional class is significantly lower than the Hausdorffdimension of the Hobby class (see Table 2).

Table 2 Mean Hausdorffdimension of Hobby class and Profi class

	Hobby class	Profi class
Average Hausdorffdimension	1.107	1.054
Standard Deviation	0.042	0.046
95%- confidence intervall	0.021	0.023

Climber Nr.223 was the best climber among the contestants and the only one who reached the finals of the Profi class (see Figure 10). However, he got a Hausdorffdimension of 1.12, which is even well above the average value of the Hobby class. He was the slowest climber of both classes with a holding time of 12.96 s therefore increasing the Hausdorffdimension. The maximum total force climber 223 exerted on the climbing hold was 350 N. This was significantly lower than the maximum force of 570 N climber 506 needed to do the move, although both climbers were approximately of the same size and weight. So, there is a difference in climbing style: climber 506 climbs quickly and needs a lot of force while climber 223 climbs very slowly but without a lot of force. This indicates that the Hausdorffdimension needs an improvement as it increases much more by a longer holding time than it decreases by the use of less force.

VI. CONCLUSIONS

As rock climbing became more and more popular in recent years, various efforts have been made to measure the forces a climber is exerting on a climbing hold and developing objective parameters for assessing the climbing efficiency. However, all these measurement had been done under laboratory conditions on a climbing wall especially equipped with instrumented climbing holds. This is due to the fact that all those instrumented climbing holds were cable based systems and the installation of these systems is rather tedious. It is nearly impossible to install the cables on an existing climbing wall without damaging the climbing wall by drilling additional holes.

To overcome this limitation an instrumented climbing hold has been equipped with a wireless data acquisition system. The climbing hold could be mounted very easily within some minutes and -even more important- there was no cabling, which could be damaged by an athlete accidentally. Therefore measurement could be done during a local climbing competition and the climbing efficiency parameters described in scientific literature could be validated with real world data.

During this competition the athletes had to climb thirteen different climbing routes with five to six hold each and only one instrumented climbing hold was installed. Additionally, it was not possible to measure the weight of the athletes, the maximum force level, the size or the technical skills. The only objective criteria available was the rank of the athletes in the competition after having tried or climbed thirteen climbing routes.

There is a 90% probability that there is a positive correlation between the Hausdorffdimension and the rank of the contestant in the competition. Considering the neglection of some very important parameters like weight or size, this is a very high probability. There is one significant outlier. The climber Nr 512 placed on the third rank had the highest Hausdorffdimension. The Hausdorffdimension of climber Nr.512 was increased by small vibrations of the exerted force.

The instrumented climbing hold proved to be able to measure the forces climbers exerted during a competition. Most of the climbers even did not notice the measurement system. This was due to the wireless data acquisition ViFDAQ and no wires neither for power supply nor for data transfer were necessary.

During a climbing contest it was not possible to get any data like size, weight and climbing experience of the contestants. So, additional measurements will be done with a test group where all this criteria are known. Additionally, a whole climbing route will be equipped with instrumented climbing holds in a further project.

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ACKNOWLEDGEMENT

This work was partially funded by the FFG - Austrian Research Promotion Agency under the project number 83927. Special thanks to Christian Grübler for the valuable help in starting this project.