Introduction of a Measurement System for Quantitative Analysis of Force and Technique in Competitive Sport Climbing

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Abstract: Rapid development and progress in competitive sport climbing lead to increasing media attention and appreciation in the sports world. Therefore, the increase of requirements to climbing athletes are unavoidably. The next step to replace existing and objective training methods, is the digitalization in terms of development of suitable measurement systems. By determining the distribution of forces as well as analysing technique, the presented method enables the evaluation of athlete's performance. With the aid of this combined system - composed of multiple 3-axis high-precision force sensor embedded climbing holds and a marker-less motion capturing framework - and a depending on the needs and application designed user-interface, coaches get the opportunity to evaluate their athlete's training outcomes. This sensor technology allows us to detect magnitude and direction of measured force vectors and the associated distribution of the body weight on hands versus feet. Additionally, the recording of athlete's motion including depth information enables calculation of relevant joint angles and body's centre of gravity. This measurement system, its modification and base components, respectively, could be used among others for dynamic move analysis in bouldering or video analysis in speed climbing.

1 INTRODUCTION

The progress of sport climbing now and in the last 25 years leads to necessary changes to meet the requirements set to athletes, especially for the disciplines bouldering and speed climbing. Hence, training methods in a save and defined environment are ensured by the spread of artificial climbing gyms all over the world, which also allow highly specialized and individual training units. By the participation at the Olympic games in Tokyo 2021, climbing reaches its historical peak as competitive sport. The progress of competition by introducing a combined mode consisting of the three disciplines bouldering, speed and lead climbing demands versatile athletes and the change of existing training methods from the bottom up. Nevertheless, the evaluation of athlete's trainings mainly consist of video analysis and the personal experience of coaches. To reach the state of the art of other mass sports like cycling or running, a novel method is herewith presented to help coaches and athletes to evaluate and monitor their performance.

The typical physique of a climbing athlete differentiates massively from other sportsmen. Therefore several researches about the performance and associated factors of the slim and light constitution of climbers were done by Giles et al. (2006). Besides existing methods like the determination of the maximum finger force and the correlation with the degree of difficulty (Ferguson and Brown, 1997; Grant et al., 2001, 1996; Mermier et al., 2000), there are no approved systems for the measurement of magnitude and direction of absolute forces.

Because of the rapid development of sport climbing and the increasing attention, the digitalization of trainings methods and the enhancement of the performance is unavoidable and therefore topics of various research projects. A Swiss research group worked on instrumented climbing holds for the realization of bouldering routes and the analysis of repeatability of climbing patterns (Donath and Wolf, 2015). For that reason they used wired 6-axis force sensors, which were mounted on cover disks and inserted into a climbing wall by cutting out holes with appropriate diameter. As a result they calculated parameters like contact time or force maximum to compare them with

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different trials and athletes.

Another important aspect of analysis in climbing sport is the recording of climbing motions to calculate relevant parameters such as joint angles or centre of gravity, which will replace the manual analysis of video footage. Researches of the university of Pisa analysed kinematics of a technique used by most of all rock climbers (Artoni et al., 2017). They constructed an experimental setup in the laboratory to simulate the so-called lolotte technique. Therefore, they built a steel scaffolding with correctly placed common climbing holds and set up multiple infrared cameras to capture the motion using marker equipped athlete. The measured coordinate data of the joints where used as input for a biomechanics analysis software to determine the effects on knee and hip caused by this technique. This highly specialized research project estimates the impact on joints by using the lolotte technique and is generally not deployable in climbing.

A method described in (Iguma et al., 2020) combines five 6-axis force sensors with seven 3D motion capture cameras to a measurement system for analysis of human motions and the corresponding forces. Compared to the here described system, the Japanese researcher group works with multiple reflective markers on the body for high precise tracking of climbing motions. Hence, they were able to determined the motion conditional forces by calculating the resulting acceleration of the body's centre of gravity and compared them to the force sensor's output. Additionally, they analysed and compared the centre of mass trajectories of beginners and experienced climbers. Because of the elaborate setup of this measurement system, the usage beyond research purposes is barely realizable.

Because of the variety of athletes and the different disciplines, the flexibility of this measurement system is essential. Therefore, a collaboration with the Austrian Climbing Federation and its trainers and athletes will make a development of training methods with specialized requirements possible. This paper will present a method for describing a measurement system used for bouldering training.

2 METHOD

Compared to speed climbing, an entire evaluation of the performance of bouldering athletes is very difficult due to the variety of techniques and complexity of movements. In spite of everything there are still important and measurable parameters, which can be determined by existing, nowadays default measurement equipment. On the other hand, there are also magnitudes like athletes conditional parameters (ape index), outside influences (temperature) or unmeasurable, psychological impacts, that should be determined to complete the hereafter introduced system. Anyway, this paper will only focus on the measurement system consisting of force and motion determination. Therefore, the presented method will be split up in these two fields, where each one will be described from its setup to the usage.

2.1 Force Measurement

To implement the idea of the distribution of forces on hands and feet, a wireless force measurement system for easy integration onto artificial climbing walls is presented.

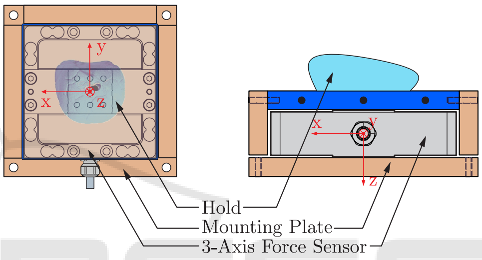

Figure 1: K3D120 3-axis force sensor with mounting box and hold.

As seen in Figure 1, the core of each instrumented climbing hold is the high precise 3-axis force sensors K3D120 from ME-Meßsysteme, which are used to measure the 3D force vector in a range of ±1kN for any axis. To protect it from outer impacts each one is surrounded by pieces of wood. At the back it is fixed on a mounting plate for an simple integration on climbing walls.

As mentioned before, the structuring of a complete wireless measurement system is essential to enable a simple installation on the walls and uncomplicated execution of trials. Therefore, the climbing holds are equipped with battery powered microcontrollers including a WiFi module. To ensure synchronicity and communication between each other, it benefits from the use of the MQTT broker/client principle. Hence, it is able to receive commands from a defined communication interface and send measured forces and other current states.

2.2 Motion Measurement

The combination of the force distribution on hands and feet and the motion of the climber expressed by the trend of joint angles as well as the position of the center of gravity and its distance to the wall ensures holistic information for analysing climbing performances. Hence, with the aid of the Realsense D435 depth camera from Intel, this system is used for the integration of the so-called Marker-less Motion Capture Method. As the title implies, the measurement and calculation of motion-specified parameters take place without any use of markers on the body of the athlete. Therefore, the athlete is not affected or disturbed by this system.

To implement the idea of marker-less motion capturing the depth camera is used to receive RGB and depth frames. After aligning them the resulting data is processed by the real-time multi-person software OpenPose (Cao et al., 2018) for the detection of human body keypoints on images or video files. By a suitable arrangement of one or more cameras it is possible to analyse the recorded motion pattern (see Figure 2).

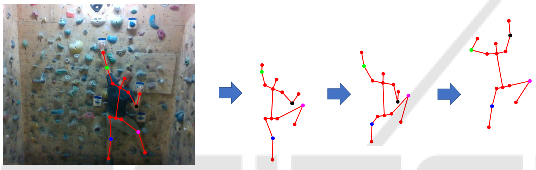

Figure 2: Example for Marker-less Motion Tracking.

Also post-processing of already recorded training trials or competitions is possible with this method. This is especially very useful for the automated analysis in speed climbing, which replaces processing by coaches. Additionally, the straightforward setup consisting of only one depth camera and the omission of any calibration and use of markers on the body enables non-invasive measurements, which incredibly increases the quality of training evaluations.

Because of the vast amount of data receiving from one trial, the focus for this paper is on the determination of the body's center of gravity and its distance to the wall as well as the distribution of the athlete's weight on hands and feet. For the calculation of the centre of gravity the weights of the single body parts and the location of their mass centres are needed. With the parameters of Table 1 the body's centre $\boldsymbol{C}$ for every frame can be determined with

$$\boldsymbol{C} = \sum_{i=1}^{12} m_i \cdot \boldsymbol{x}_i\,, \tag{1}$$

where $\boldsymbol{x}_i$ is calculated with the coordinates of the by OpenPose (Cao et al., 2018) identified joints and the corresponding radii r_i as follows:

$$\boldsymbol{x}_i = \boldsymbol{s}_i \cdot r_i + \boldsymbol{j}_{p,i}\,. \tag{2}$$

The variables s_i and $j_{p,i}$ are defined as the vector and the proximal joint of the i-th body segment.

With the recorded depth information, the hence fitted plane of the climbing wall and its normal vector are used to calculate the distance of the body centre to the wall with the dot product

$$d = (\boldsymbol{C} - \boldsymbol{P}) \cdot \boldsymbol{n}\,, \tag{3}$$

with $\boldsymbol{P}$ as any point on the plane and $\boldsymbol{n}$ as the normal vector.

Table 1: Distribution of weight and mass center radius for each body segment (de Leva, 1996).

body segment	mass m_i [%]	radius r_i [%]
Head	6.94	50.02
Trunk	43.46	44.86
Upper Arm	2.71	57.72
Forearm	2.23	67.51
Upper Leg	14.16	40.95
Lower Leg	4.33	44.59
Foot	1.37	44.15

For the results presented in the following section, both subsystems measured with a sample rate of 30 Hz. Since both measurement units are recording independently, the outcomes need to be synchronized. By logging timestamps of the operating system for the force sensors and the depth camera and assuming they run with a accuracy of ± 0.5 Hz, it suffices to compare the timestamps at the starting point of each recording and shift the delayed data set by the resulting time lag.

3 RESULTS

The above-mentioned measurement system consisting of eight climbing holds with integrated 3-axis force sensors and a marker-less motion capturing system including a depth camera, was first applied in the climbing gym 'Kletterzentrum Innsbruck' for validation purpose.

Therefore, the holds were placed on a bouldering wall at specified positions to analyse two different motion patterns (see Figure 3). The depth camera was positioned such that the starting pose as well as the whole climbing route would be visible on the recordings. The orientation of the camera was calculated using the built-in accelerometer for determination of the disposition to the wall. Three athletes with related potential were chosen to realise initially comparisons between them with the aid of body parameters (height, weight, ape-index).

In Figure 3 you can also see, that by synchronizing data of force measurement and motion capturing

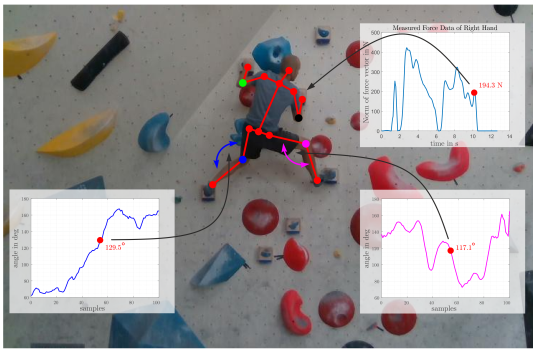

Figure 3: Snapshot of a climbing motion with illustration of force of one hold and the joint angle of both knees.

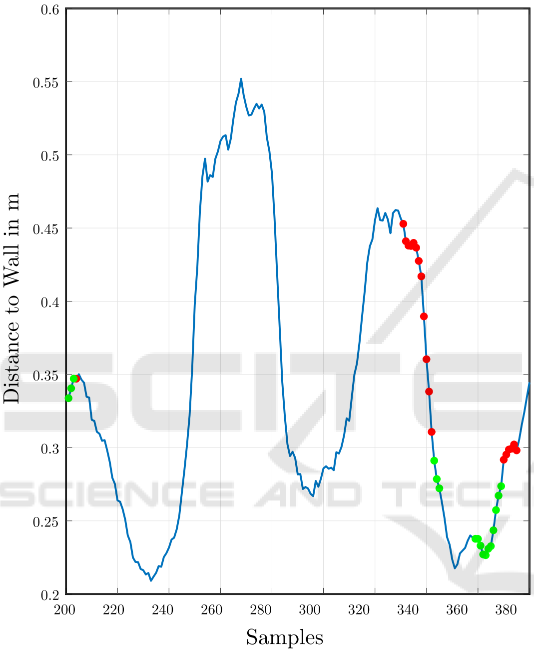

Figure 4: Distribution of the distance of the body centre to the wall for a selected area of samples.

systems, the resulting output contains a plenty of information about one climbing trial. A great benefit of this system is the complete wireless and markerless solution. Therefore the athlete is free of thoughts about any measurements. An example for the resulting characteristics of the distance to the wall for a selected range of samples is apparent in Figure 4.

The other important parameter to superficial reason the performance of athletes is the ratio of the force distribution on hands and feet. Compared to the calculation of the athlete's distance to the wall, where only the motion tracking system is used, both parts of the above presented measurement system are assigned. Therefore the integrated climbing holds are used to get the force vector for every sample. Since the recording of the force distribution is done for the whole climbing trial, the extraction of portions, where the four body segments were grabbing/booting the corresponding hold, is required. At this point the recordings of the depth camera are employed.

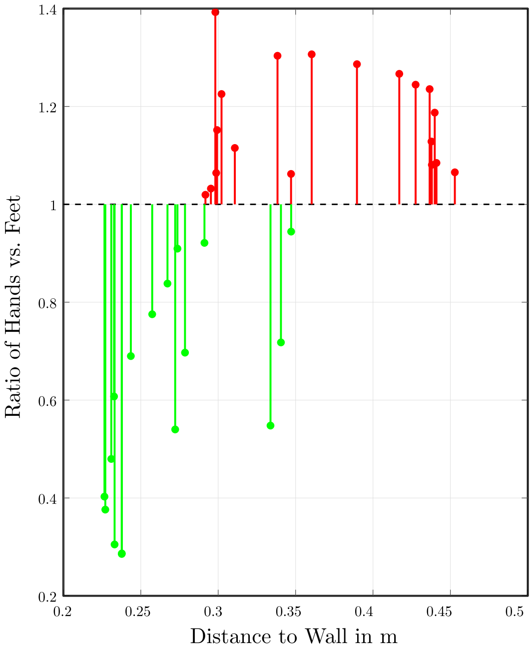

Figure 5: Relationship between body centre's distance to the wall and the ratio of force on hands and feet.

First, the location of the position of the embedded climbings holds on the wall is accomplished. Considering that a static snapshot without any athlete was gathered to mark the holds and a boundary rectangle with defined threshold around them, respectively. By using the detected joints, a implemented algorithm is able to recognize the moment of entering one of these threshold boxes by a body segment of interest and mapping them. The resulting characteristics of hands and feet, respectively, are vectorial added and normalized for every sample. The quotient of them returns the hands-versus-feet-ratio

$$R = \frac{\|\boldsymbol{F}_{\mathrm{LH}} + \boldsymbol{F}_{\mathrm{RH}}\|}{\|\boldsymbol{F}_{\mathrm{LF}} + \boldsymbol{F}_{\mathrm{RF}}\|},$$

with $\boldsymbol{F}_{\mathrm{LH}}$, $\boldsymbol{F}_{\mathrm{RH}}$, $\boldsymbol{F}_{\mathrm{LF}}$, $\boldsymbol{F}_{\mathrm{RF}}$ as the force vectors of hands and feet. An indicator for good and energy efficient performance is a ratio $R < 1$, whereby the body weight is shifted towards the feet.

To ensure this condition a decrease of the distance of the body's centre of gravity to the wall is required. In Figure 4 and 5 a correlation of this value and the ratio R is visible. Figure 5 represent the relationship between them and marks the efficient samples with green and the poorer ones with red dots. Except of few outliers the condition $R < 1$ is met within a reduction of the body centre's distance to the wall.

The calculation of the distance of the athletes centre of gravity to the wall and the associated measurement results are highly dependent of accuracy of the depth information of the used camera system. Therefore for these first climbing trials, the optimal positioning of the depth camera was essential to avoid environmental influences like light and reflections.

4 CONCLUSION

Herewith a new method to open up new perspectives for the specific force and technique evaluation in competitive sport climbing was presented. This system implements simultaneous measurements of force and motion with the possibility to evaluate athlete's performance by analysing parameters like the distance of mass centre of the body to the wall or the hands-versus-feet-ratio. On the other hand you can also use the measured force vectors and captured joint angles for the study of early identification of injuries or fatigue by evaluating the repeatability of multiple climbing trials. Minor modifications of the existing system (enlargement of the sensors housing for the use of bigger holds, usage of a mobile tracking camera system, etc.) enable an enhancement of the area of application. Of course, systems using a marker-based measuring system increase the accuracy of motion-dependent parameters. The non-use of markers on the athlete's body prevents invasion on their technique while measurements, but also creates a dependency of the used camera system and its positioning. On that account the above mentioned modifications will be implemented as well as the usage of the lidar (light detection and ranging) camera Realsense L515 from Intel to get among other things a better accuracy of the depth information, which is essential for the validity of this measurement system.

Working in a cooperation with the 'Kletterzentrum Innsbruck' and the Austrian Climbing Federation and its national trainers on two further projects in the field of bouldering and speed climbing will also lead to a advancement of the described method. Therefore the presented measurement system is modified in such way, that e.g. equipping larger holds with multiple connected force sensors could enabled dynamic move analysis ('Dyno', jumps).

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