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Methods for quantitative evaluation of force and technique in competitive sport climbing

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Abstract. Increasing media attention of and progress in competitive climbing demand for novel solution in sport analysis to accompany and contribute to the evolution of climbing. We present a holistic approach to acquire movements in sport climbing. Knowledge on force and corresponding body motion helps to understand technique, performance and might even lead to injury prevention during training. Our system allows detection of peaks in force on each climbing hand and foot hold while recording the associated body position and motion. To achieve this, we equipped each hold with a three-axis force sensor and combined this with a three-dimensional markerless motion capture system based on a depth camera. Existing methods to determine finger strength and other parameters such as temperature are employed to ensure comparable and repeatable results. In addition, pre-assesement of athletes will be used to evaluate inter- and intra-individual variability among athletes.

1. Introduction

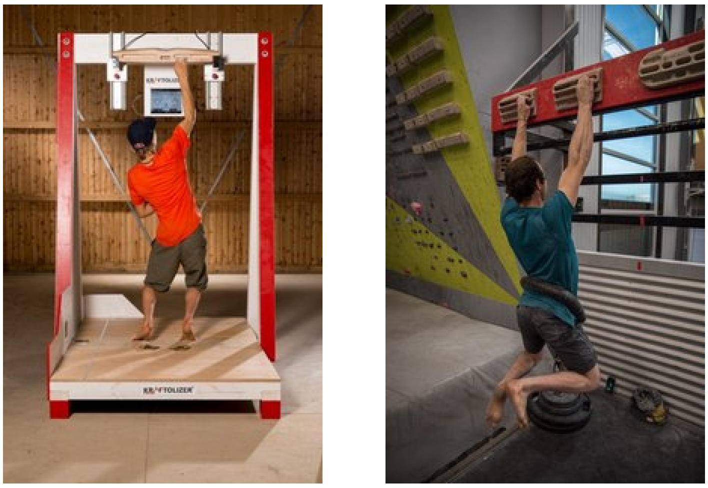
Rapid changes and growth of the climbing sport from an unknown niche towards mass and competition sport are clearly visible during the last 15 years. Artificial climbing gyms are nowadays widely spread and offer a save and defined environment for training. Climbing athletes are therefore capable to concentrate on complex motion sequences and aimed weight training to evolve the climbing sport. Other factors indicating the fast development are the increase from the native six to 12 degrees of difficulty established by the UIAA (Union Internationale des Associations d'Alpinisme) as well as the heavily increase of media attention and progress in competition. Starting with growth of participating nations since the first world cup in 1991, climbing as a competitive sport reaches its historical peak with the inclusion to the Olympic games in Tokyo 2020.

Thus, the requirements for athletes are increasing. In comparison to the initial competitive problems focusing on physical strength and stamina, athletes nowadays are required to add large amount of coordination and technique to their strength and stamina skill. This complexity presents trainer and athlete with new challenges. Hence, coaches try to support exercises by using video analysis tools and help with personal experience.

Except of the isolated way of determining the maximum force of fingers by hanging on a defined holds, their are no objective measurement methods up to date. Therefore, the following presents a new method for measuring and evaluating force and motion during climbing trials.

2. State of the art

Typical climbing athletes are distinguished from other sportsmen by a slim and light body structure with muscular torso, whereby the performance and related factors have been topics of various studies [1]. As mentioned before, finger strength is usually used as a limiting factor, though different studies showed inconsistent results regarding the correlation of maximum finger strength and degree of difficulty [2, 3, 4, 5]. Measurement of the maximal strength of fingers is mostly achieved by static, single-handed exercises (figure 1a) or, alternatively, using both hands and additional weights (figure 1b).



(a) (b)

Figure 1. Typical methods for determining finger force; (a) measuring one-handed traction [6]; (b) both-handed with additional weight. [7]

Similar to this, the quantitative determination of the strength endurance is done by using the maximum time hanging on a defined hold as a parameter.

Compared to other mass sports like cycling or running, where measurements of critical parameters to increase the personal performance got indispensable, the development of the climbing sport in respect thereof is backward, but with rising trend. Accordingly, new methods to support evaluation and monitoring are important to improve this sport. Moreover, no quantitative methods exist to detect injury risks during training.

3. Method

The holistic evaluation of the performance of athletes in climbing sport is due to its complexity nearly impossible. Parameters like mental strength and its influence on the performance are not quantifiable. Compared with this, the force and technique as well as outside influences (temperature, humidity, etc.) are of today's standards measurable. Therefore, the presented method should support the development of the climbing sport and can be separated in following branches:

- pre-investigation of athletes
- determination of environmental impact
- direct measurement of forces during climbing
- tracking of joint motion during climbing.

3.1. Pre-Investigation

An independent dataset for a period of substantial length and different athletes is essential for the validation of the method and comparability and signification of the results. Thus, to quantify inter- as well as intra-athletes-variability, pre-investigations are necessary:

- *Defined and individual warm-up* is important to ensure a comparable degree of performance
- *Physiology* as size, weight, resting heart rate, etc.
- *Isolated maximum finger force* by existing methods
- *Environmental factors* like temperature or humidity for possible correlations with performance
- *Questionnaire* to find not measurable factors

3.2. Measurement of forces during climbing trials

Existing methods shown in figure 1 are based on isolated, climbing-unspecific trials. Therefore, we are presenting for the first time a direct method for measuring force while climbing. Three-axis force sensors (K3D120) from *ME-Meßsysteme* are used to determine forces on holds during climbing (figure 2a).

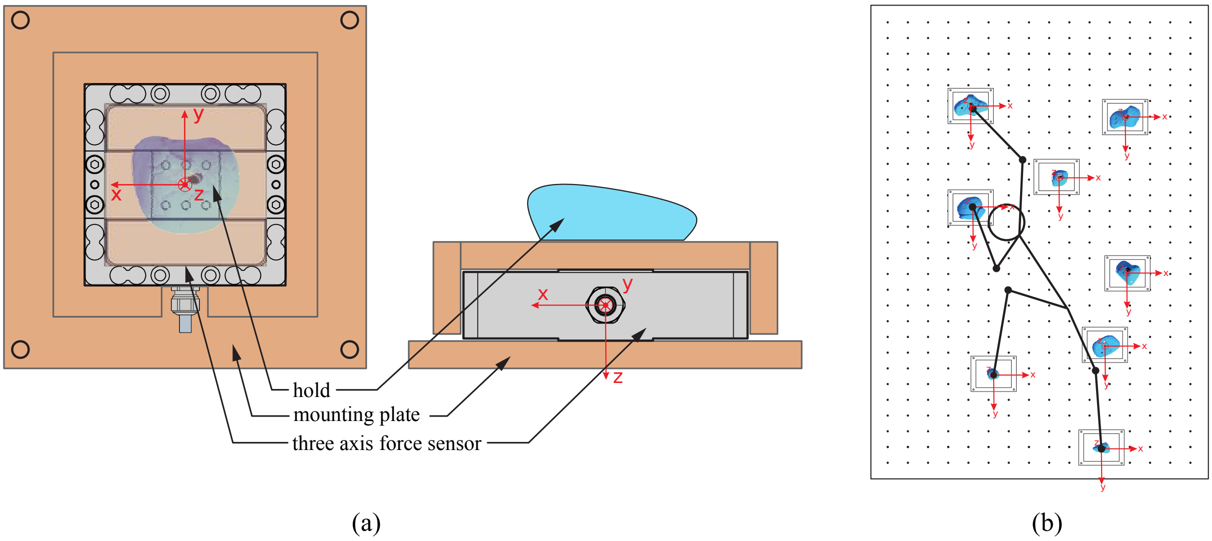


Figure 2. (a) Three-axis force sensor (gray) with mounting plates (brown) and hold (blue); (b) Synchronous recording of motion of all joints and force distribution.

The outer plates are designed for an easy integration into existing artificial climbing walls. Another key part of the measurement system is the analog to digital conversion as well as the amplification of the output of the sensor. It is important to capture all three axis of every single sensor synchronously. High-precision amplifiers and AD-converters are employed, which allow the digitalization of all channels with 12-bit-resolution. For the case of integration and handling, the system is compact, battery powered and wireless. Thus, the system is equipped with microcontrollers featuring embedded WiFi module. According to a server/clients principle one of these microcontrollers serves as an access point and saves the incoming data of the clients off-site.

3.3. Determination of motion during climbing trials

Knowledge about the distribution of forces between single limbs is very important for the evaluation of strength as well as technique. To understand the cause of this distribution it is necessary to measure both force and current body position with all joints. For the first time a depth camera is employed, that enables the following:

- synchronous images and force measurements
- determination of position of body and joints
- measuring the climbers distance to the climbing wall

This challenges are solved by modifying the so-called *Markerless Motion Capture* Method using a RealSense D435 modular unit from *Intel*. Figure 2b describes exemplary the process using *Markerless Motion Capture*. In our case, we use the Realsense depth camera to obtain a RGB and depth frame for every snapshot and evaluate the data using *OpenPose* [8] software to jointly detect human body keypoints. Hence, it is possible to record and analyse a motion pattern. The advantage over classic video analysis is the possibility to determine automatically joint angles and the distribution of force as a consequence thereof.

4. Results

During initial experiments, we evaluated the ability of a *Markerless Motion Capture* system and a prototype of a force sensor embedded climbing hold to track joints and measure forces during movement in three dimensions. Figure 3 shows a frame captured with the Realsense D435 during moving patterns. In a next step the position of the joints are calculated off-line by processing the taken RGB frames with *OpenPose*. As a result we get pixel coordinates of all relevant human body joints, which are used afterwards to get corresponding three-dimensional coordinates by analysing the related depth frames. Thus, we obtain after simple vector calculations, the joints angles over time (see figure 3). Concurrently,

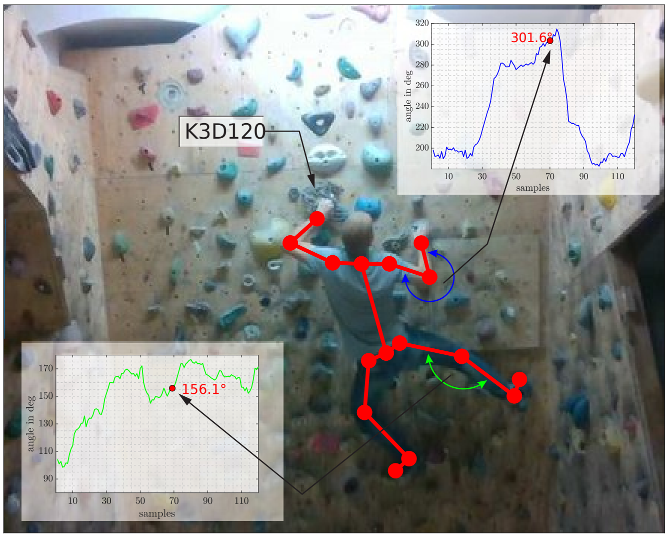


Figure 3. Rendered sample of the moving pattern including joints position and the time course of the right elbow and knee angles.

the integrated force sensor measures all three parts of the force vector simultaneously and sends the data leadless to the computing hardware.

Figure 4a illustrates the result of forces in all three directions during our first climbing trials. The hold was mounted to a inclined climbing wall at an horizontal angle of 45 degrees to strain all axes of the sensor. The force amplitudes corresponding to the momentary movement in figure 3 are marked with red dots.

We can determine the moment of first contact with an initial rise in force. Furthermore, the peaks illustrate among others the force necessary to readjust the hand position on the climbing hold. After readjusting the hand we see varying forces during the repositioning of the body until the moment of exiting the climbing hold.

To get comparable results, we repeated three different moving patterns several times in a row with the same athlete. Figure 4b represents for every axis the resulting differences for each time step and four trials. Due to the variation in climbing speed, the results were post-processed to compare measurement amplitudes. The remaining motion sequences were compared with the first try and time wrapped to recognize similarities.

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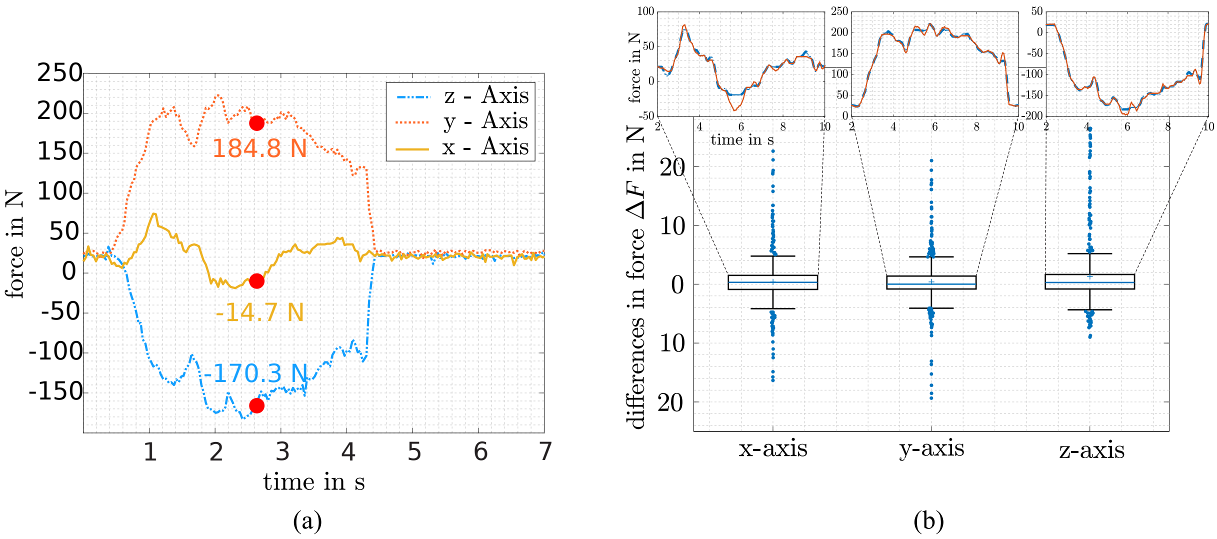

Figure 4. (a) Force vector measured with the K3D120; (b) Time wrapped signals of first and third try (on top) and differences in force plotted for all three axes.

With respect to a few outliers, the outcome of this analysis shows that the climber was able to repeat nearly the same exercise for four times.

5. Conclusion

The introduced results illustrate the working principle of the in this paper presented method for simultaneous measurement of forces and motion capturing to detect human body keypoints. An evaluation of the outliers in figure 4b with the greatest deviation would be the next interesting step. Possible reasons for this significant variance could be different angles of joints while grabbing the sensor hold or signs of fatigue. To get an understanding of this changing factors, an extension of the existing system by adding more sensor holds and an enlargement of data sets by performing further iterations of the same moving pattern will be done for multiple athletes.

The received data sets of force sensor and motion capturing system will enable further studies on improving technique, performance and injury prevention of climbing athletes.

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