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Short communication

Dynamic force measurements for a high bar using 3D motion capturing

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ABSTRACT

The displacement of a calibrated horizontal bar is used as a measure for forces acting on the bar itself during dynamic performances in artistic gymnastics. The high bar is loaded with known forces and the displacement is monitored by means of a *Vicon* motion capturing system. The calibration results are fitted according to the Euler–Bernoulli beam theory. After calibration, forces can straightforwardly be measured by multiplication of the bar displacement with the determined fit parameter. This approach is also able to account for non-central force application (two hands on the bar) and the effect of the bar's inertia. Uncertainties in measured forces are assessed to be ±25 N plus an additional 1% for the unknown weight distribution between the two hands.

1. Introduction

Measurement and knowledge of time-dependent forces acting on the athlete during performances on the high bar are of high relevance for better understanding of an athlete's physical requirements and abilities as well as for studying, modeling, and optimizing different exercises. Different studies aimed to model and optimize such gymnastic movements on the horizontal bar (Hiley and Yeadon, 2005, 2008), others tried to describe the energetic processes during different exercises (Arampatzis and Brüggemann, 1999, 2001), but little information about forces during such high bar performances is available in the literature. Force measurements from bar mounted strain gauges were presented in Arampatzis and Brüggemann (1999). There, two different systems (at different framing rates) have been used to record the strain gauge readings and video data. The new approach presented within this work uses only one single system for all measurements, which eliminates such synchronization related errors as described in Lipfert et al. (2009).

The aim of this study was to deploy a *Vicon* 3D motion capturing system not only for tracking and analysis of an athlete's performance on the high bar but also for dynamic force measurements of that same exercise. Tests indicated that the spatial resolution of a *Vicon* system is sufficient to detect the bar displacement with a precision and accuracy needed to use the bar itself as a dynamometer. This approach only needs one system to be set up and further facilitates data evaluation as all data is recorded with the same system and renders subsequent data synchronizations unnecessary. Additionally, the effect of the high bar's inertia can be addressed since forces, displacement vectors, and derivatives thereof are available.

2. Methods

A *FIG* conform horizontal bar (Fédération Internationale de Gymnastique—Apparatus Commission, 2006) was set-up and centered within a *Vicon* V612 motion capturing system (Oxford Metrics Ltd, UK) with 8 M2 near-infrared cameras operating at 100 Hz. The (Cartesian) coordinate origin was set in the center-of-mass of the horizontal bar itself. The calibrated 3D volume covered 3 m in *x*-direction (axis through bar), 5.5 m in *z*-direction (height), and 6 m in *y*-direction (length). For the purpose of bar displacement calibration a set of 45 reflective markers (spherical, 14 mm diameter) was attached to the horizontal bar; 23 markers were evenly distributed on top of the bar, 22 markers were attached to the lower side of the bar.

Instead of actually hanging weights from the bar to create a displacement, a digital tension balance (Rauch KHW 500, Rauch, Austria, calibrated with exactly known weights (±3 g)) was mounted in the strap/ratchet system loading the bar using tensile forces (see Fig. 1). The use of this balance: (a) allowed application of large forces in any direction, (b) avoided possible mistakes due to friction of bearings and pulleys, (c) avoided oscillations due to the inertia of weights, and (d) facilitated the installation for the calibration. The bar displacement was calibrated by means of different known forces ranging from 100 N up to 4000 N (in steps of about 250 N) in two orthogonal directions (*y*- and *z*-directions) and for three different tensions of the high bar tension cables. The three studied tensions represent the range of tensions typically used and were descriptively named 'slack', 'medium', and 'stiff'.

2.1. Fit function

According to the Euler–Bernoulli beam theory (e.g., Han et al., 1999; Fließbach, 1999) we choose the following fit function for the bar displacement $\delta(x,F)$:

$$\delta(x,F)=\delta^{ref}(x)+\delta^{app}(F)+\delta^{bar}(x,F)=(b+cx)+AF+aF[l^3-6lx^2+4x^3 sgn(x)] \qquad (1)$$

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This fit function consists of three terms: $\delta^{ref}(x)$ accounts for a possible shift of the apparatus with respect to the coordinate system and includes the two fit parameters b and c, $\delta^{app}(F)$ accounts for any possible force-dependent displacement of the entire apparatus excluding the bar (the fit parameter A contains the elastic properties of the apparatus), and $\delta^{bar}(x,F)$ expresses the actual displacement (in either y- or z-direction) for a given load F at a position x along the bar; the fit parameter a is determined by the second moment of area and Young's modulus of the bar; $sgn(x)$ is the sign function.

Eq. (1) results in individual fit coefficients $k(x)$ representing the bar displacement in [N mm^{-1}] for both calibrated directions:

$$k(x) = \frac{1}{A + a[l^3 - 6lx^2 + 4x^3\,sgn(x)]} \tag{2}$$

Exemplarily, the resulting 3D contour for different loads and the respective displacements ('medium' cable tension) is shown in Fig. 2.

2.2. Fit procedure

For each direction and cable tension we average the marker position over the 3 s recording range. A least-squares fit of the resulting 260–660 points to Eq. (1) is then performed. The weights of each data point are determined from the 3D reconstruction residual of the marker and the uncertainty of the applied forces.

In order to find estimates for the uncertainties of the fit parameters A, a, b, c as well as k we apply a statistical bootstrap procedure (Efron, 1979) with 200 bootstrap samples for each direction and cable tension.

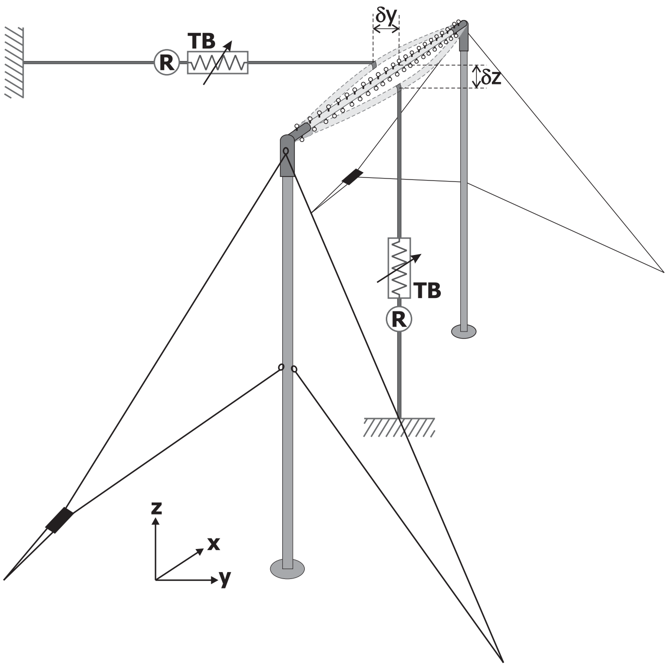

Fig. 1. Sketch of the high bar illustrating the actual marker positions as well as the strap/ratchet mechanism that was used to displace the bar in y- and z-directions during calibration. For ease of viewing, the 45 markers (23 on top of the bar, 22 at the bottom) are only shown for the high bar at resting position, but not for the displaced bar. The strap is attached to the bar on one side and anchored to the floor/wall on the other side. R …ratchet, TB …tension balance, $\delta y/\delta z$ …displacement in y- and z-directions.

2.3. Corrections

Non-central force application: forces during typical dynamic exercises are rarely applied centrally in a single point but will usually be applied at the position of the athlete's hands. Typical grip positions for giant swings during this investigation were found to be ±20 cm from the center of the bar (*COB*). The corrected bar displacement for two forces F_1 and F_2 positioned at a distances x_1 and x_2 with respect to the *COB* is calculated by the following equation with a being the fit parameter from Eq. (1) (see Table 2):

$$\delta^{bar}(x,F_1,F_2) = a\sum_{i=1}^{2} F_i\left(\frac{1}{l}(l+2x)(l-2x_i)(l^2-2l(x-x_i)-2(x^2+x_i^2)) + 4(x-x_i)^3(1+sgn(x-x_i))\right) \tag{3}$$

Inertia of the bar: the effective mass μ of the bar is estimated by using free oscillations of the bar after dismounts. Bar inertia contributions according to $\mu\ddot{\vec{r}}$ can be calculated (after appropriate filtering) and need to be subtracted from the measured forces.

3. Results

The calibration coefficients at the origin for the three studied tensions are listed in Table 1. A continuous trend towards smaller ratios of the calibration coefficients in y- and z-direction, k_y/k_z, with increasing stiffness of the tension cables is observed. Unsurprisingly, higher tensions at the cables do have a larger influence on the y as on the z-direction (additional contribution from bar supports). To calculate the displacement for any other position along the bar further information about the fit parameters A and a is needed. The summarized results for the three tensions are listed in Table 2.

When working with athletes the individually set tension of the cables has to be determined by probing the displacement of the bar with one known force in y- and z-direction, respectively. Therefore, we hung a weight of about 600 N for displacement in z-direction and loaded the pre-existing strap/ratchet system (see Fig. 1) for a displacement in y-direction with roughly 1000 N; this was completed during the athlete's warm-up routine. As a test for this procedure, we used the body weight of an athlete (65.4 kg). The weight measured by means of the bar displacement was 65.1 kg, under-estimating the weight by only 0.5% (despite the uncertainty estimate of ±25 N, see Section 3.1).

As an example for the practical application of this force measurement based on the bar displacement, forces measured with two markers during a backward giant swing (*GS*) of an elite

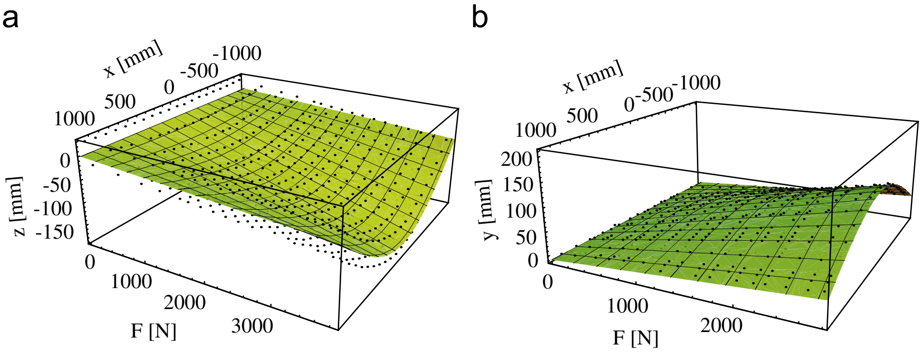

Fig. 2. Displacement of the high bar during calibration with different loads for the calibrated z- and y-directions. Black dots indicate the position of the markers and the contour represents the fitted displacement results for the centerline of the bar. Since the markers were attached on top of and below the bar their positions are higher or lower than thefitted centerline contour. The center of the bar is at $x=0$. (a) Calibration: z - and (b) y-axis.