A Dynamic Force Analysis System for Climbing of Large Primates

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Abstract

Registering substrate reaction forces from primates during climbing requires the design and construction of customized recording devices. The technical difficulties in constructing a reliable apparatus hinder research on the kinetics of primate locomotion. This is unfortunate since arboreal locomotion, especially vertical climbing, is an important component of the hominoid locomotor repertoire. In this technical paper, we describe a custom-built climbing pole that allows recordings of dynamic 3-dimensional forces during locomotion on horizontal and sloping substrates and during vertical climbing. The pole contains an instrumented section that can readily be modified and enables us to register forces of a single limb or multiple limbs in a broad range of primates. For verification, we constructed a similar set-up (which would not be usable for primates) using a conventional force plate. Data for a human subject walking on both set-ups were compared. The experimental set-up records accurate and reliable substrate reaction forces in three orthogonal directions. Because of its adjustability, this type of modular set-up can be used for a great variety of primate studies. When combining such kinetic measurements together with kinematic information, data of great biomechanical value can be generated. These data will hopefully allow biological anthropologists to answer current questions about primate behaviours on vertical substrates.
Introduction

Much of our basic understanding of human locomotion results from both kinematic (body movement) and kinetic (ground-reaction force) data. These data are used for determining, for example, spatiotemporal gait parameters [Alexander, 1977a, b], determinants for human bipedal gait [Saunders et al., 1953] and the inverted pendulum and spring mass models of human locomotion [Cavagna et al., 1963, 1964; Winter, 1990; Farley and Ferris, 1998]. Experimental set-ups consisting of a 3-dimensional motion capture system and a 3-dimensional force plate are standard in human gait laboratories [Winter 1990; Alexander, 1992; Farley and Ferris, 1998].

Set-ups including ground-reaction force analysis have also been used for non-human primate species [Kimura et al., 1977; Yamazaki and Ishida, 1984; Demes et al., 1994; Schmitt, 1999; D’Août et al., 2002], elucidating the basic biomechanics of their locomotion as well.

However, the habitual locomotor modes of nearly all primates are arboreal, not terrestrial [Cartmill, 1985; Preuschoft, 2002]. Although several studies have addressed the biomechanics of arboreal locomotion in primates (kinematics of vertical climbing [Hirasaki et al., 1992, 1993, 2000; Isler, 2002, 2003]; muscle activity of vertical climbing [Fleagle et al., 1981; Vangor and Wells, 1983; Larson and Stern, 1986; Hirasaki et al., 1995; Stern and Larson, 2001]), only a few include substrate reaction force (SRF) measurements [Yamazaki and Ishida, 1984; Hirasaki et al., 1992, 1993, 2000; Demes et al., 1995, 1999; Schmitt, 1995, 2003; Lemelin and Schmitt, 2003; Schmidt, 2005]. For hominoids, basic data other than kinematics [Isler, 2002] are scattered, and combined kinematic/kinetic data are scarce [Yamazaki and Ishida, 1984]. However, these data are essential for a more detailed understanding of primate arboreal locomotion. Additionally, vertical climbing is particularly interesting in light of the evolution of hominid bipedalism [for a review, see Schmitt, 2003]. Many authors have suggested that vertical climbing may be the precursor of bipedalism and the predominant locomotor mode of the immediate ancestor of bipedal hominids [Tuttle, 1969; Tuttle et al., 1975; Prost, 1980; Fleagle et al., 1981; Isler, 2002, 2003; but see Gebo, 1996; Richmond and Strait, 2000; Richmond et al., 2001; for a review, see Schmitt, 2003].

Calibrated, high-resolution set-ups are not realistic in the wild and even in captivity technical difficulties have hindered research on the kinetics of primate climbing. First, arboreal locomotion is highly variable [Doran, 1996; Preuschoft, 2002]. Climbing (as a general term) refers to any kind of locomotion on supports with vertical or inclined surfaces [Cartmill, 1985]. This includes going up or down, vertically or on a sloping support, with or without hand assistance, etc. Since displacements in the arboreal habitat are not only vertical, but also horizontal and predominantly oblique, it is essential to explore the change from horizontal walking to vertical climbing [Nakano, 2002; Preuschoft, 2002]. Therefore, an appropriate experimental set-up should be able to address climbing at different slopes and with different substrate diameters. Second, 3-dimensional substrate reaction forces have to be measured accurately. The climbing structure should be long enough to allow for more than one complete stride. This may, in the case of large animals, impose serious mechanical requirements upon the equipment. Third, the apparatus developed to measure forces during bonobo climbing should be able to manage climbing
of almost all primate species. Last, the set-up should be operational in zoo and laboratory environments.

This paper describes a new experimental set-up for the study of primate climbing and validates the quality of its output under realistic conditions. In the future, a full data set of bonobo climbing at different substrate inclinations will be presented.

Materials and Methods

Construction of the Experimental Force Pole
The construction of the force pole has to meet certain requirements. First, the construction has to withstand severe impacts and must be rigid and stiff enough to make precise measurements. Second, the change in inclination of the device and the adjustment of the substrate diameter should be relatively easy to accomplish. Because worst-case scenario impact forces (forces applied by a 100-kg individual jumping from 7 m height and landing on the set-up with an impact time of 0.25 s) are approximately 5,670 N, a problem of deformation would occur if a distance of 4 m is spanned with one pole of small diameter. Therefore, the device is made of a 4-metre steel H-shaped supporting beam (HEA 140, 133 mm × 140 mm) with a maximal deformation of 0.008 m and maximum acceptable load of approximately 36,500 N in parallel with a second I-shaped beam (IPE 80, 80 mm × 48 mm) with a maximal deformation of 0.003 m and a maximum acceptable load of approximately 9,400 N serving as the actual climbing surface (further referred to as the climbing pole). Vertical bars of 170 mm in height (or 80-mm bars at the level of the force transducers that are 90 mm high) with two parallel plates (90 mm × 90 mm) on either side connect both beams. Figure 1 illustrates these requirements.

In order to register SRFs of separate hands and feet, the climbing pole is divided into 3 segments (1.60, 0.40 and 2.00 m) of which the middle section is instrumented with two Kistler (9367B) 3-dimensional force transducers (fig. 1). The segment is long enough to measure forces of a complete foot or hand contact and is small enough to reduce the chance of double foot/hand contacts. By covering the I profile all round with wood, the climbing surface becomes circular with a diameter of 120 mm (fig. 1). To register climbing sequences on a range of slopes between 0 and 90°, the instrumented pole can be shifted inside two 4-metre-long U profiles, one fixed to the wall and another fixed to the ground.

The force transducers have to be able to withstand severe impacts applied by free-ranging bonobos and, especially, have to perform precise measurements. The Kistler 9367B transducers have a measuring range (calibrated range up to 10 kN for Fx, Fy and up to 40 kN for Fz) sufficient for measuring SRFs of normal climbing sequences (less than 1,000 N). The worst-case scenario forces of 5,670 N do not exceed the transducer’s allowed overload.

Two Kistler charge amplifiers (5038A) are built into one side of the H profile to convert the transducer signal (charge, in picocoulombs) into a tension (in volts). The amplifiers are provided with a 15-volt DC power supply. Six signals are led to a data acquisition card (A/D converter, National Instruments 6023-E) installed in a standard PC.

Data Acquisition System
To sample SRFs, the acquisition programme ABAS (Arboreal Bonobo Analysis System) was written in Labview 6.1 (National Instruments). This programme reads the 6 uncalibrated force signals in volts (2 transducers, each X, Y and Z) from the amplifiers. The signals are synchronously sampled at a scan rate of 1,000 Hz and a sample definition of 12 bits. All measuring channels are set at 300 N/V in Measurements and Automation Explorer (National Instruments). A pole fixed frame of reference is used in which Y is in the direction of the pole, Z is perpendicular to the longitudinal axis of the pole and X is the lateral component. Recordings start manually immediately before the subject contacts the climbing pole and last for 5 s. After recording, ABAS graphically shows the force signals on a screen for visual inspection and data are automatically written to an ASCII file.
Data Analysis

Natural frequencies for the vertical and mediolateral directions of the pole are determined by vertical and lateral hammer impacts to the middle of the instrumented section.

To obtain the overall X, Y and Z force, the corresponding X, Y and Z signals of each transducer are summed and the resulting SRF calculated by vector summation. Raw SRF data are filtered at a cut-off frequency of 10 Hz with a 4th-order zero phase shift Butterworth low-pass filter. Force profiles are resampled to 201 data points (= intervals of 0.5% of total contact time). Each new data point is calculated from the neighbouring original data points by linear interpolation.

Verification of the Measurements

To verify the accuracy of our measurements, a similar second set-up is constructed. This consists of a longitudinally halved wooden pole (120 mm diameter), identical to the one used to cover the climbing pole, mounted on top of a conventional gait lab force plate (AMTI OR 6-5-2000). This is built into a 2.5-metre-long walkway and the construction is set at an angle of 30°.

SRF measurements of a volunteer trained gymnast were made on the two set-ups at an inclination of 30°. The test person walked upwards and performed 15 bipedal sequences per set-up holding his arms horizontally for balance. He reported that the task felt subjectively the same in both set-ups and similar contact times were found. The subject’s performance on both systems was at comparable speeds. The last 4 sequences on both set-ups were compared, allowing the test person to accommodate to each of the set-ups.

Results

Physical Properties

Natural frequencies are approximately 22 Hz in all directions which is high enough to filter the measurements with a low-pass filter since the frequency of the signals needed to describe climbing in bonobos is about one order of magnitude
Fig. 2. Example graph of unfiltered signal (thin line) versus filtered signal (thick line). Filtering with a 4th-order zero phase shift Butterworth low-pass filter at a cut-off frequency of 10 Hz removes noise due to natural frequency of the set-up (22 Hz) without loss of signal (2 Hz).

Fig. 3. Comparison of vertical (Fz) and fore-aft (Fy) SRFs of a trained gymnast walking bipedally on two analogue set-ups at a 30-degree inclination. Black: new climbing set-up using Kistler (9367B) transducers; gray: test set-up using a conventional AMTI (OR 6-5-200) force plate. The average of 4 foot contacts of each system is described with standard errors.
lower (2 Hz). Figure 2 shows that filtered data represent the unfiltered signal well without loss of essential information.

**Verification of the Measurements**

The results of the comparative study are plotted in figure 3. This figure shows that the vertical (Fz) and fore-aft (Fy) SRF components measured on the instrumented pole are similar to measurements of the test set-up, indicating that the equipped pole measures accurately. Lateral (Fx) SRF components are left out because their amplitudes are negligible, as expected. An impact peak at the beginning of each sequence is found in SRFs of both set-ups but is more distinct in the climbing pole set-up. This dissimilarity might be due to the piezo-electric technology (Kistler) in the instrumented pole, which responds better to fast force gradients than the strain gauge technology in the AMTI force plate.

**Discussion**

The system described here for analysing the kinetics of bonobo climbing is able to execute accurate and reliable measurements. The natural frequency is high enough to filter the data with a low-pass filter without losing any essential information.

This set-up was installed in the bonobo indoor hall in the Wild Animal Park of Planckendael (Belgium), where 8 bonobos are housed. The animals habituated to the pole quickly and climbed voluntarily on the set-up. To use the set-up more frequently, most animals were trained to follow a light projected by a laser pointer. After intensive use of the pole by the animals and unfavourable conditions such as moisture and temperature fluctuations, the pole has been proven to operate in real-life conditions.

For an easy altering of inclination, U profiles are used to change the inclination from 0 to 90°, with angles at choice in between. Moreover, this set-up is useful for studying all climbing primates. The force transducers are designed to measure forces between 0 and 40,000 N with a 0.01-newton threshold. The diameter of the climbing surface can be adapted by changing the wooden cover attached to the I profile into one with a smaller or bigger diameter. The instrumented middle part can be made shorter or longer dependent on the animal’s foot/hand size. The set-up can be used in zoo and laboratory environments.

The set-up is, of course, a simplification of the natural habitat, but a biomechanical study like this is impossible to conduct in the wild and has to be done under normalized circumstances, with a straight pole and a perfectly known inclination. Nevertheless, personal observations of climbing are consistent with observations of bonobo behaviour in the wild [Susman et al., 1980; Susman, 1984; Kano, 1992; Pontzer and Wrangham, 2004] where arboreal locomotion is the main mode of locomotion.

The design of our apparatus is inspired by Yamazaki and Ishida [1984] and Hirasaki et al. [1993, 2000], where individual limb reaction forces during climbing in gibbons and Japanese macaques, respectively, and spider monkeys on vertical substrates were measured. Other studies using vertical arboreal substrates are those of Demes et al. [1995, 1999], reporting a set-up built to quantify total force produced...
by Malagasy clingers and leapers during take-off and landing, and of Vinyard and Schmitt [2004], describing their multifunctional apparatus used for measuring forces during clinging, gauging and possibly climbing. Horizontal poles for registering reaction forces similar to our set-up are reported in Schmidt [2005] and Schmitt [1995]. Both authors registered individual limb reaction forces during horizontal quadrupedal walking in small animals. The studies mentioned above have provided new valuable insights into the arboreal locomotion and behaviour of primates. Our set-up enables us to expand the data set with information of the largest primates, namely the great apes. In addition, our apparatus can measure SRFs at different inclinations between 0 and 90°.

In the future, research will be comprised of SRF measurements and synchronized video recordings at different inclinations between 0 and 90°, to explore the changes from horizontal walking to vertical climbing. This will elucidate differences in kinematic parameters, substrate reaction forces and external moments generated at the joints. In addition, the results will be integrated with data from a parallel study dealing with terrestrial bipedal and quadrupedal locomotion in bonobos [Aerts et al., 2000; D’Août et al., 2001, 2002].

For decades, quantifying SRFs has been essential for providing information about the dynamics of terrestrial locomotion in primates. We hope that applying a similar technique to understand the dynamics of primate climbing promises to lead to a more complete understanding of current hypotheses as to which type of locomotion was the precursor of habitual bipedalism in hominids.

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References


