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A cycle ergometer mounted on a standard force platform for three-dimensional pedal forces measurement during cycling

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Abstract

This report describes a new method allowing to measure the three-dimensional forces applied on right and left pedals during cycling. This method is based on a cycle ergometer mounted on a force platform. By recording the forces applied on the force platform and applying the fundamental mechanical equations, it was possible to calculate the instantaneous three-dimensional forces applied on pedals. It was validated by static and dynamic tests. The accuracy of the present system was −7.61 N, −3.37 N and −2.81 N, respectively, for the vertical, the horizontal and the lateral direction when applying a mono-directional force and −4.52 N when applying combined forces. In pedaling condition, the orientation and magnitude of the pedal forces were comparable to the literature. Moreover, this method did not modify the mechanical properties of the pedals and offered the possibility for pedal force measurement with materials often accessible in laboratories. Measurements obtained showed that this method has an interesting potential for biomechanical analyses in cycling.

Keywords: Cycling; Pedal forces; Force platform

1. Introduction

Cycle ergometers are used in laboratories for training and testing purposes (e.g. Denis et al., 1982; Hautier et al., 2000; Lepers et al., 2000; Linossier et al., 1993) and also for basic investigations concerning muscular efficiency (Gaesser and Brooks, 1975; Sidossis et al., 1992; Whipp and Wasserman, 1969). In these studies, mechanical work done when pedaling is of interest and can be accurately measured (Arsac et al., 1996; Lakomy, 1986). Moreover cycle ergometers are also used for research questions where the knowledge of pedal forces is useful, as for pedal forces asymmetry investigations (Daly and Cavanagh, 1976) or comparison of shoe-pedal interfaces (Wheeler et al., 1992). So it is important to accurately measure pedal forces. For that purpose, different systems were proposed.

Previous studies analyzed pedal force in one dimension, using either strain gauges fixed on the crank (Daly and Cavanagh, 1976; Künstlinger et al., 1984; Sargeant and Davies, 1977) or directly under the pedal to measure the normal force (Brooke et al., 1981; Hoes et al., 1968). However, these did not allow for an inverse analysis where intersegmental loads can be computed.

Then pedal forces measurements in two dimensions (Beelen et al., 1994; Gregor et al., 1985; Newmiller et al., 1988; Patterson et al., 1983; Rohmert and Krell, 1980; Soden and Adeyefa, 1979) and complete three-dimensional (3D) pedal force investigations (Boyd et al., 1996; Hull and Davis, 1981; Ruby and Hull, 1993; Ruby et al., 1992; Stone and Hull, 1993) were performed using strain gauges fixed under the pedals. Furthermore piezo electric transducers fixed under the pedal for 3D pedal force measurement were proposed in the literature (Broker and Gregor, 1990; Ericson et al., 1985).

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However, these methods based on forces transducers fixed under the pedal are not widely available and pedal force investigations could be more accessible without the need of these specialized force pedals.

The aim of this study was then to develop and validate a new measurement system that allows 3D pedal force measurement with often an accessible force platform. For that purpose, the pedals and gear mechanism were separated from the bicycle frame and were fixed on a force platform.

2. Material and methods

2.1. Mechanical device

A typical friction-loaded cycle ergometer (Monark type 818E, Stockholm, Sweden) was equipped with specific transducers according to Arsac et al. (1996). The friction force applied by the tension of the belt that surrounded the flywheel was measured by means of a strain gauge (FGP Instrumentation type FN3030 0–20 daN, les Clayes sous Bois, France) previously calibrated by a known mass (5 kg) hung on the friction belt and in an unloaded condition to give the 0 value The strain gauge non-linearity was below 0.3%. The flywheel displacement was calculated with an accuracy of 11,815 pts per pedal revolution (gear ratio of 52:14), thanks to an incremental encoder (Hengsler type RI32-0-100 AR11, 2 channels, 100 pts/turn, Aldingen, Germany) fixed on a castor (∅65 mm) linked to the flywheel. The distance traveled by a point on the rim of the flywheel was 6 m for one pedal revolution, allowing a simple conversion from angular to linear velocity. So, the flywheel displacement measurement was also provided with an accuracy of 1969.2 pts.m^{-1} of linear displacement. The rear horizontal position of the right pedal could be detected by a magnetic transducer (Omron type E2EG-X5MB1, Fontenay sous Bois, France). The crank length was 0.17 m. The mass and the radius of the flywheel were 22.5 kg and 0.26 m, respectively. To obtain an accurate measurement of the flywheel inertia, the method proposed by Lakomy (1986) was used. In this study, the linear relationship between friction and deceleration was: friction = 14.5 deceleration−2.76 ($r = 0.99$). Thus the linear flywheel inertia equivalent (I_{eq}) expressed in kg was 14.5 kg as previously reported by Morin and Belli (2004). The force to overcome the flywheel inertia (F_I) as a function of time was then calculated as follows:

$$F_I(t) = I_{eq} \cdot a(t), \quad (1)$$

where a (m.s^{-2}) was the linear acceleration of a point located at the flywheel periphery.

In conventional units, where force is expressed in Newtons per metre and acceleration in radians per second squared, this equation indicated a moment of inertia of 0.9802 kg.m^2 for the flywheel of the Monark 818E.

In order to obtain an isolated mechanical system, the pedal and the gear mechanism were separated from the bicycle frame and tightly fixed on a force platform (Kistler type 9281B, Wintertur, Switzerland) by means of a specially designed steel part providing high stiffness and rigid connection. The bicycle frame, including flywheel and friction system was fixed aside from the force platform (Fig. 1) in order to avoid any mechanical contact with the gear mechanism nor the steel part and in such a way that the original dimensions of the whole bicycle were maintained.

The force platform used was equipped with four piezo-electric transducers measuring each 3D forces applied (i.e. the medial–lateral direction x, the anterior–posterior direction y, the vertical direction z). The resonant frequency of the force platform with the pedals and gear mechanism fixed (total mass of 90 kg) was 51 Hz (when hitting the upper surface of the force platform with a 0.4 kg hammer while force signals were sampled at 200 Hz). According to data provided by the manufacturer, linearity and hysteresis values were respectively $\leqslant \pm 0.5\%$ and $\leqslant 0.5\%$. The cross-talk data were: $F_z \rightarrow F_{x,y} \leqslant \pm 1\%$; $F_x \leftrightarrow F_y \leqslant \pm 1\%$; $F_{x,y} \rightarrow F_z \leqslant \pm 2\%$.

Signals from the strain gauge, displacement encoder and position transducer were sampled at 200 Hz on a PC computer via a specially designed interface card including a strain gauge signal conditioner (Analog Device 1B31AN, Norwood, Mass, USA), a 12 bit A/D converter (Analog Device AD574AJD, Norwood, Mass,

Fig. 1. The cycle ergometer mounted on the force platform for 3D pedal force measurement. The bicycle was equipped with a displacement transducer (a), a force transducer (b) and position transducer (c).