Effects of Vertical Alignment of Leg on the Knee Trajectory and Pedal Force during Pedaling

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Objective: This study evaluated the vertical and horizontal forces in the frontal plane acting on a pedal due to the vertical alignment of the lower limbs.

Method: Seven male subjects (age: 25.3 ± 0.8 years, height: 175.4 ± 4.7 cm, weight: 74.7 ± 14.2 kg, foot size: 262.9 ± 7.6 mm) participated in two 2-minute cycle pedaling tests, with the same load and cadence (60 revolutions per minute) across all subjects. The subject's saddle height was determined by the height when the knee was at 25° flexion when the pedal crank was at the 6 o'clock position (knee angle method). The horizontal force acting on the pedal, vertical force acting on the pedal in the frontal plane, ratio of the two forces, and knee range of motion in the frontal plane were calculated for four pedaling phases (phase 1: 330°–30°, phase 2: 30°–150°, phase 3: 150°–210°, phase 4: 210°–330°) and the complete pedaling cycle.

Results: The range of motion of the knee in the frontal plane was decreased, and the ratio of vertical force to horizontal force and overall pedal force in the complete cycle were increased after vertical alignment.

Conclusion: The ratio of vertical force to horizontal force in the frontal plane may be used as an injury prevention index of the lower limb.

Keywords: Pedal force, Joint movement, Frontal plane

INTRODUCTION

Pedaling force is converted into rotational movement through the pedal crank. Pedaling can largely be divided into two phases: the pedal lowering phase and pedal pull-up phase. The cycle is propelled forwards with the repeated combination of pressing, pulling, and pushing during each pedaling cycle. When observed from the frontal plane, the perpendicular lower limb force exerted on a pedal can prevent potential injuries and overexertion by aligning the knee and the pedal to be vertical (Sanner & O'Halloranet, 2000). Since pedaling is a process of repetitive movements, an exertion of force in an improper posture can cause injuries (Pruitt & Matheny, 2006). Fitting is usually performed in order to improve the pedaling capability and reduce the risk of injuries. Fitting can largely be divided into two areas. First, static fitting is a method that changes the saddle height according to the user's body type. Second, dynamic fitting induces vertical alignment by inserting a wedge in the shoes depending on the status of varus and valgus to effectively convey and maximize lower limb force to the crank. Varus and valgus refer to the medial and lateral positioning of the metatarsal bones. Normally, the transmission of the lower limb force to the crank occurs at the metatarsal bones, which are in direct contact with the pedals. The metatarsal curvature produces an unnecessary space with the sole of the foot and causes lateral angulation of the knee during pedaling, reducing the efficiency of vertical force transmission and therefore negatively affecting pedaling (Garbalosa et al., 1994).

Representative preceding studies that confirmed the effects of wedges include a study by Dinsdale & Williams in 2010, which confirmed the increase in pedal power with wedge application in patients with varus or valgus positioning, and the study by Choi et al. in 2012 that confirmed the increase in maximal contact, average contact, maximal contact pressure, and average contact pressure in different foot areas with the use of wedges. Furthermore, the study by Choi et al. in 2012 confirmed the maintenance of constant power with the use of wedges, where the use of wedges induced alignment of the lower limbs and affected variables such as knee angulation, pedaling power, and average speed. As shown above, kinematic analysis such as vertical alignment and mechanical analysis such as pedaling power are commonly conducted. These studies indicate the need for fitting considering any varus and valgus positioning. Although most studies confirmed the effects of vertical alignment using indirect variables such as pedaling power and foot pressure, there is a need for a direct evaluation using the force exerted on the pedals by the lower limb while taking into account varus and valgus. In addition, the index of effectiveness (IE) is a representative variable used to evaluate the effectiveness of pedaling in the sagittal plane. IE is expressed as a
proportion of the resultant force (RF), which is a vector sum of the forces exerted to both the pedals and the vertical force, and effective force (EF), which is the vertical force on the crank (Lafortune & Cavanaugh, 1983). However, since IE confirms the effectiveness of pedaling solely in the sagittal plane, it does not take into account the influence of horizontal forces caused by knee angulation.

Therefore, this study aims to quantitatively confirm the forces exerted on the pedals while wearing wedges. Prior to the study, vertical alignment of the lower limb was expected to be induced by wearing the wedges, and this was in turn expected to lead an increase in the vertical force exerted on the pedals. To verify this, a frontal index of pedaling efficiency was presented to quantitatively express the effective force on the pedals through the proportion of vertical and horizontal forces.

**METHODS**

1. Participants

Seven male adults with no musculoskeletal abnormalities who could perform pedaling normally participated in this study. The participants’ characteristics are shown in Table 1. All participants were informed of the details of this study, and their written consent was obtained before conducting the experiment. Approval from the Research Ethics Committee was obtained before the study (7001355-201506-HR-062).

<table>
<thead>
<tr>
<th>Subject characteristics</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>Age (years)</th>
<th>Foot size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height (cm)</td>
<td>175.4 ± 4.7</td>
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<td>262.9 ± 7.6</td>
</tr>
</tbody>
</table>

2. Measurement

All experiments were performed using a fixed commercial road bicycle (Wilier, La Triestina Lampre, 700 × 23c, Italy) with rollers. A 3D motion analysis system (Motion Analysis, USA) composed of six cameras was used to measure joint angulation, pedal location, and pedal reaction force. A self-developed three-axis pedal reaction force meter (hysteresis: ±0.5%, nonlinearity: ±0.5%; Lee et al., 2014) was used at 120 and 1,200 Hz sampling frequencies (Figure 1). A metronome was used to maintain a pedaling cadence of 60 revolutions per minute and an SRM power meter (Schoberer Rad Messtechnik, Germany) were used to regulate power. In order to use cycling shoes with cleats in the experimental condition, shoes with cleats were attached to the self-developed three-axis reaction force pedals. All participants used identical types of shoes.

3. Processing

In order to determine the number of wedges to be inserted, the participants’ varus or valgus angles were measured as shown in Figure 3a. The wedge consisted of a thin piece of plastic used to fill the empty space below the metatarsal bones. There are two types of wedges used for varus and valgus. Based on Bike Fit Systems (Bike Fit Systems LLC, USA), one 2 mm thick wedge was used in participants in case of the valgus or varus angles between 3~7° and 1~2 wedges were used in participants with varus or valgus angles between 6~12° (Table 2). Since each participant’s characteristics were different, the knee angle in the sagittal plane was set to 25° when sat on the saddle and the pedal was at the lowest position using Holmes knee angle method in order to conduct the experiment in identical conditions (Holmes et al., 1994). All participants performed 10 minutes of warm-up stretches prior to the