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ORIGINAL

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 Bae et al. in 2013 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 1. Subject characteristics

Subject characteristics	Height (cm)	175.4 ± 4.7
	Weight (kg)	74.7 ± 14.2
	Age (years)	25.3 ± 0.8
	Foot size (mm)	262.9 ± 7.6

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.

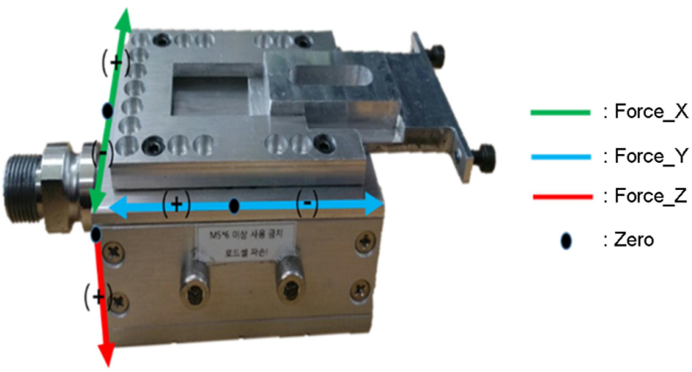


Figure 1. Pedal force plate.

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 varus or valgus 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

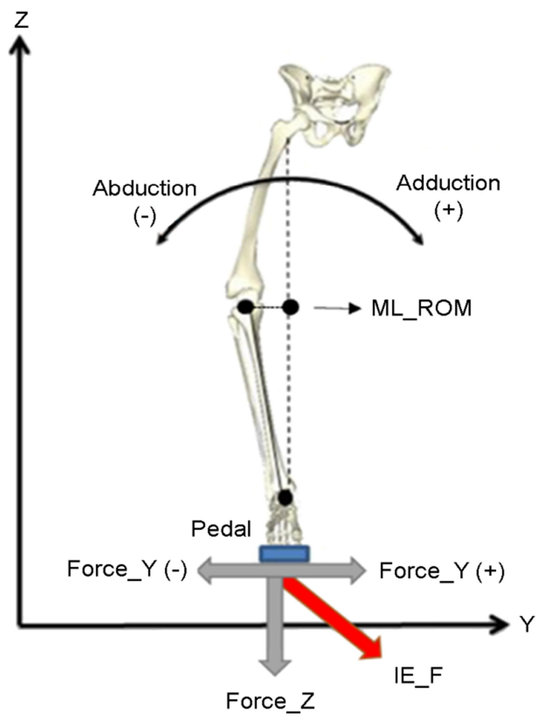
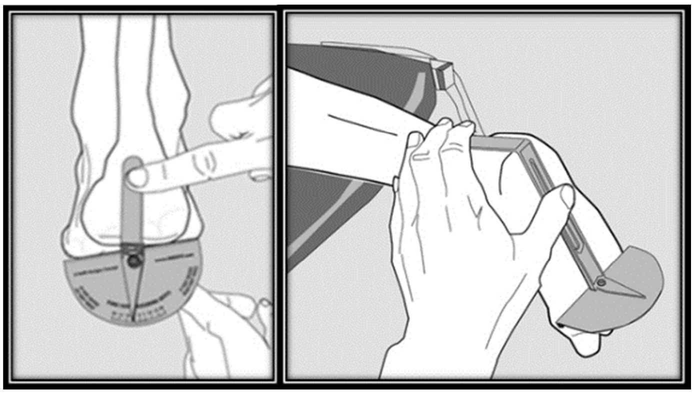


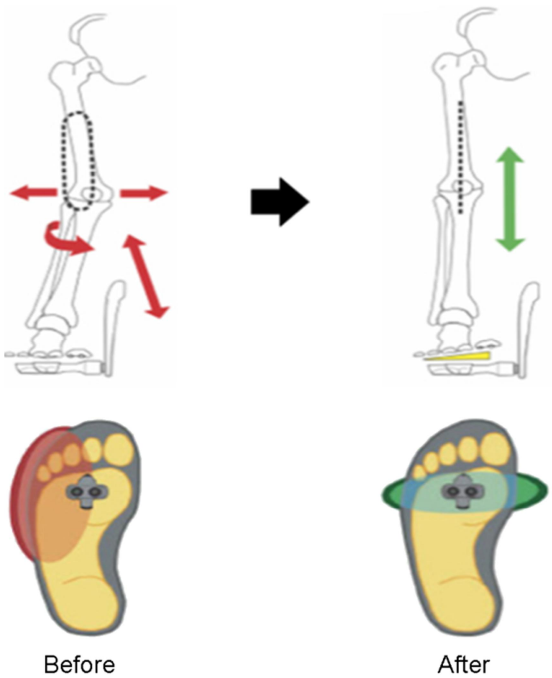
Figure 2. Knee range of motion and pedal Force in the frontal plane.

Table 2. Angles of varus and valgus and the number of wedges

Subject	Varus or valgus (°)				Number of wedges			
	Varus		Valgus		Varus		Valgus	
	L	R	L	R	L	R	L	R
1	–	3	5	–	–	1	1	–-
2	–	5	–	–	–	1	–	–
3	–	3	–	–	–	1	–	–
4	–	6	3	–	–	1	1	–
5	–	6	4	–	–	1	1	–
6	5	–	–	3	1	–	–	1
7	3	4	–	–	1	1	–	–



(a) Measurement of varus and valgus



(b) Before and after using wedges

Figure 3. Measurement of varus and valgus and differences between the wedges (BIKEFIT).

experiment. To investigate the changes in the knee joints depending on the use of wedges, reflective markers were placed on the lateral aspect of both the right knee and right ankle joints. The results were then analyzed with a 3D motion analyzer. In addition, to measure the crank angles during pedaling, markers were placed on the center of the pedals and the bottom bracket, at the crank's center of rotation. Knee movement in the frontal plane is shown in Figure 2. All participants performed two sets of 2-minute long pedaling trials at 60 rpm. A 30-minute break was allocated in between the tests.

4. Data analysis

Only the data obtained during the middle 1-minute of the 2-minute test were used for analysis, excluding 30 seconds from the beginning and end of the 2 minutes. In order to eliminate noise, a 2nd order zero-lag Butterworth filter was used with a 6 Hz cutoff frequency. All variables were divided into four phases (phase 1: 330~30°, phase 2: 30~150°, phase 3: 150~210°, phase 4: 210~330°) and a complete rotation (0~360°) based on the rotational position of the crank (Top=0°) prior to analysis (Figure 4). The difference between the ankle marker and the knee marker was defined as the range of knee motion in the frontal plane (ML_ROM) and calculated from the measured data. In addition, the IE in the frontal plane (IE_F) was calculated using the integral sum of both the vertical force (Forces_Z) and horizontal force (Force_Y) in each phase from the pedal force measured with the pedal reaction force system (Eq. 1). All data analyses were performed using MATLAB R2013a (Mathworks Inc., USA).

$$\mathrm{IE\_F} = \int_{r1}^{r2} \mathrm{Force\_Z}\,dr / |\pm \mathrm{Force\_Y}\,dr|$$

Eq 1. Calculation of IE_F
(r^1: start angle of the region of interest, r^2: end angle of the region of interest).

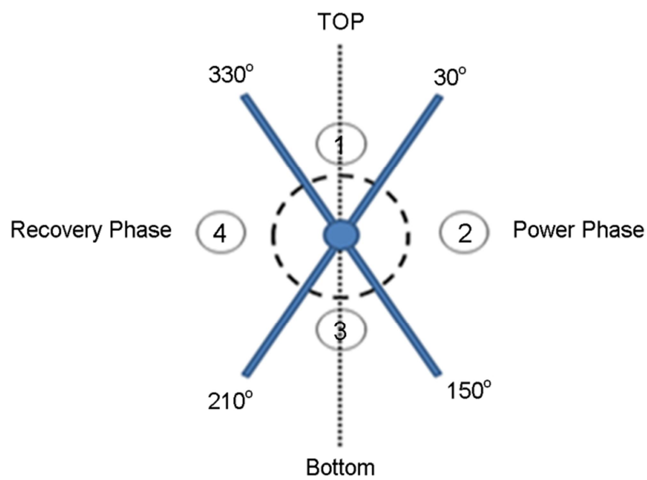


Figure 4. The definition of pedaling phases.

Table 3. Knee range of motion in the frontal plane by phase (ML_ROM), Force_Y, Force_Z, and frontal plane IE (IE_F)

Right Leg		Without wedge	With wedge	*p*-value
Phase 1	Force_Y (Σ_N)	195.02 ± 66.95	215.68 ± 64.67	0.397
	Force_Z (Σ_N)	4101.71 ± 818.42	4571.70 ± 1148.38	0.064
	IE_F	23.44 ± 8.13	22.82 ± 7.31	0.646
	ML_ROM (mm)	14.79 ± 9.65	15.02 ± 9.11	0.812
Phase 2	Force_Y (Σ_N)	1126.69 ± 251.02	1209.51 ± 285.90	0.391
	Force_Z (Σ_N)	11153.34 ± 1833.94	11779.91 ± 2036.83	0.075
	IE_F	10.24 ± 2.00	10.09 ± 1.89	0.811
	ML_ROM (mm)	26.45 ± 15.90	24.00 ± 15.58	0.051
Phase 3	Force_Y (Σ_N)	152.33 ± 70.29	131.95 ± 48.68	0.254
	Force_Z (Σ_N)	1808.01 ± 733.92	1832.95 ± 828.93	0.839
	IE_F	13.42 ± 5.95	14.16 ± 5.61	0.685
	ML_ROM (mm)	10.79 ± 7.72	11.44 ± 7.83	0.471
Phase 4	Force_Y (Σ_N)	476.27 ± 275.63	431.28 ± 149.43	0.498
	Force_Z (Σ_N)	2906.18 ± 1147.59	3045.99 ± 1093.38	0.048*
	IE_F	6.00 ± 1.72	6.95 ± 1.55	0.076
	ML_ROM (mm)	24.01 ± 12.30	20.92 ± 12.10	0.074
Complete rotation	Force_Y (Σ_N)	1950.31 ± 367.96	1988.43 ± 384.41	0.35
	Force_Z (Σ_N)	19969.24 ± 4328.11	21230.55 ± 4858.96	0.056
	IE_F	10.28 ± 1.56	10.70 ± 1.66	0.027*
	ML_ROM (mm)	39.52 ± 20.34	37.59 ± 20.17	0.037*

5. Statistical analysis

Statistical analyses for the frontal plane range of motion of the knee, pedaling power, and IE_F were performed using SPSS v22 (IBM Co, USA). A paired *t*-test was conducted with a significance level of $\alpha=0.05$.

RESULTS

The results of the frontal plane range of motion of the knee, pedaling power, and IE_F are shown in Table 3. With the use of wedges, the range of motion of the knee increased by 0.23 mm and 0.65 mm in phases 1 and 3, respectively. Although the range of motion of the knee decreased by 2.45 mm and 3.09 mm in phases 2 and 4, respectively, the changes were not statistically significant. The range of motion of the knee showed a statistically significant decrease of 1.93 mm ($p=0.037$) during the complete rotation. With the use of wedges, the horizontal force on the pedal increased by 20.66 N, 82.82 N, and 38.12 N in phase 1, phase 2 and complete rotation, respectively. Although the horizontal force increased by 20.38 N and 44.99 N in phases 3 and 4 without the use of wedges, the changes were not significant. With the use of wedges, the vertical force on the pedal increased by 469.99 N, 626.57 N, 24.94 N, and 1261.31 N in phase 1, phase 2, phase 3, and complete rotation, respectively. However, no statistically significant change was observed. Only phase 4 showed significant increase of 139.81 N ($p=0.048$). Without the use of wedges, IE_F was increased by 0.62 and 0.15 in phases 1 and 2 respectively. Although IE_F increased by 0.74 and 0.95 in phases 3 and 4 while using wedges, no statistical significance was confirmed.

Only complete rotation showed a significant increase of 0.42 ($p=0.027$).

DISCUSSION

The goal of this study was to quantitatively investigate the pedaling effectiveness by measuring pedaling forces with or without the use of wedges. Taking into account the participants' different leg lengths, the saddle heights were modified to give all participants a knee angle of 25° using a knee angle method (Tamborindeguy & Bini, 2011) and a cadence of 60 revolutions per minute was maintained. Furthermore, cleats were used to confine the feet at the center of the pedal. All modifications were made to provide identical experimental conditions for all participants and accurately compare the changes in vertical alignment and pedaling power.

The results of this study showed that pedaling power increased with the use of wedges except for horizontal forces in phases 3 and 4.

Although IE_F increased in phases 1 and 2 without the use of wedges and in phases 3 and 4 when using wedges, the changes were not statistically significant. However, IE_F significantly increased when using wedges in the complete rotation.

Approximately 95% of the population has either a varus (approximately 86.7%) or valgus (approximately 8.8%) positioning. Therefore, the physical characteristics of human body impede the optimal vertical alignment in the trajectory of lower limbs while pedaling (Garbalosa et al., 1994). Varus or valgus positioning can cause unnecessary spaces between the foot and the shoe, which restrict the complete transmission of physical power to the pedals through the crank. This limitation can be compensated with the wedges. A representative study that confirmed the effectiveness of wedges (Sanner & O'Halloran, 2000) reported that the wedges vertically aligned the knee and pedal, and therefore reduced any potential loss of power. Furthermore, a previous study (Dinsdale & Williams, 2010) confirmed an increase in pedaling power with the use of wedges (Figure 3b). In this study, the effects of wedges on the range of motion of the knee in each phase were investigated. Although no statistical differences were observed, the wedges induced greater vertical alignment in the complete rotation. The results indicated that wedges caused vertical alignment in the complete rotation rather than in a specific phase.

A previous study on the effects of wedges using mechanical variable foot pressure distribution reported that the average contact pressure, maximum contact pressure, average contact, and maximum contact of the forefoot on the pedal increased with the use of wedges (Bae et al. 2013). The results of this study also indicated that although the horizontal force showed no significant changes, it increased in the complete rotation, phase 1, and phase 2 with the use of wedges. An increase in horizontal force was observed in phases 3 and 4 without using wedges. The vertical force was increased in all phases while using the wedges and a significant increase was especially observed in the recovery phase, phase 4 (Table 3). The increase in horizontal and vertical forces in the complete rotation indicated that the wedges compensated for the unnecessary space between the foot and the shoe caused by any present varus or valgus, and increased the amount of force applied to the pedals.

In this study, IE_F, which is a ratio of vertical and horizontal forces in the frontal plane, was not significant in any one phase. However, IE_F was significantly increased in the complete rotation with the use of wedges. No significant changes were observed when the vertical force and the horizontal force were confirmed separately. Therefore, the pedaling effectiveness cannot be explained with horizontal and vertical forces. IE_F is a ratio between the vertical and the horizontal forces and was significantly increased when using the wedges with a significant decrease in the frontal range of motion of the knee curing a complete rotation. The results indicate that IE_F is a variable that is directly influenced by the application of force on the pedals. Therefore, an increase in IE_F is correlated with pedaling effectiveness caused by vertical alignment of the lower limbs.

An increase in IE_F and decrease in the frontal plane range of motion of the knee in a complete rotation were confirmed. Cycling injuries and alignment of the lower limbs are closely related (Pruitt & Matheny, 2006) and studies have reported that cycling injuries were caused by repetitive pedaling motion (Callaghan, 2005). Furthermore, a previous study investigated the correlation between the history of cycling injuries and excessive movement of the knee (Hannaford et al., 1986). Although injuries are usually caused by excessive use of the knee, improper alignment of the lower limbs, and consequent improper weight bearing, increase the risk for injuries (Holmes, Pruitt, & Whalen, 1994; Pruitt & Matheny, 2006). Therefore, alignment of the lower limbs during pedaling is important for prevention of knee injuries. The frontal plane pedaling index of effectiveness proposed by this study could be used as a reference for further studies on injury prevention. In further studies, the effects of frontal wedges on knee weight bearing should be investigated using the changes in muscle activation and body modeling in order to identify variables involved in injury prevention.

CONCLUSION

The range of motion of the knee in complete rotation was significantly decreased with the use of wedges. However, the IE_F, which represents pedaling effectiveness, and vertical forces on the pedals significantly increased. The results indicate that the use of wedges reduces the misalignment of the lower limbs caused by varus or valgus positioning. Therefore, the pedaling effectiveness is improved with reduced dissipation of power. Wedges also induce proper posture and consequently prevent injuries.

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