Cycling Kinematics in Healthy Adults for Musculoskeletal Rehabilitation Guidance

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Abstract

Background: Stationary cycling is commonly used for postoperative rehabilitation of physical disabilities, but few studies have focused on the three-dimensional (3D) kinematics of rehabilitation. This study aimed to elucidate the three-dimensional lower limb kinematics of musculoskeletally healthy people and the effect of sex and age on kinematics using a controlled bicycle configuration.

Methods: Thirty-one healthy adults participated in the study. The stationary cycle positioning was standardized using the LeMond method by setting the saddle height to 85.5% of the participant's inseam. The participants maintained a pedaling rate of 10–12 km/h, and the average value of three successive cycles of the right leg was used for analysis. The pelvis, hip, knee, and ankle joint motions during cycling were evaluated in the sagittal, coronal, and transverse planes. Kinematic data were normalized to 0–100% of the cycling cycle. The Kolmogorov-Smirnov test, Mann-Whitney U test, Kruskal-Wallis test, and k-fold cross-validation were used to analyze the data.

Results: In the sagittal plane, the cycling ranges of motion (ROMs) were 1.6° (pelvis), 43.9° (hip), 75.2° (knee), and 26.9° (ankle). The coronal plane movement was observed in all joints, and the specific ROMs were 6.6° (knee) and 5.8° (ankle). There was significant internal and external rotation of the hip (ROM: 11.6°), knee (ROM: 6.6°), and ankle (ROM: 10.3°) during cycling. There was no difference in kinematic data of the pelvis, hip, knee, and ankle between sexes ($p = 0.12$ to 0.95) and among ages ($p = 0.11$ to 0.96) in all anatomical planes.

Conclusions: The kinematic results support the assertion that cycling is highly recommended for comprehensive musculoskeletal rehabilitation. These results may help clinicians choose a target recovery ROM based on healthy and non-elite individuals and issue suitable guidelines to patients.

Background

Musculoskeletal rehabilitation programs provide extensive orthopedic rehabilitation post-surgery or injury. Rehabilitation helps patients to regain muscle and joint function and to restore bone health by building strength and restoring flexibility and mobility, which reduces pain. Bones and joints in humans weaken with aging [1], and many countries are becoming aging societies. Thus, musculoskeletal rehabilitation is of considerable importance.

Stationary cycling is commonly recommended for individuals with a variety of disabilities, such as knee osteoarthritis, anterior cruciate ligament (ACL) reconstruction, and total hip arthroplasty. Cycling reduces the load on the knee joint [2, 3] and ACL [4–7]; the tibiofemoral compressive forces during cycling are between 0.3 and 2 times the body weight, while other full weight-bearing rehabilitative exercises (e.g., walking, stair ascent/descent) generate forces of approximately 2–4 times the bodyweight [4, 8, 9]. The patellofemoral compressive force [9, 10], shear stress [11], tibiofemoral shear force [12], and ACL strain [9, 10, 13, 14] are low during cycling, yet the quadriceps and hamstring muscles are strengthened as knee stability increases [7, 11, 15–17]. Pedaling also increases the range of motion (ROM) of the hip, knee, and ankle joints [15, 18–20].

Many studies have investigated joint kinematics during cycling, but most have been conducted on patients with orthopedic disabilities [11, 14, 21]. Few studies have performed kinematic research on healthy individuals. Furthermore, when healthy study subjects were examined, they were high-level or experienced cyclists [22–26], and the study did not focus on target ROMs for rehabilitation purposes. Additionally, most studies analyzed two-dimensional kinematic data and focused on the sagittal plane joint kinematics during cycling [1]. The three-dimensional (3D) kinematic data from musculoskeletally healthy individuals can serve as a clinical guide for appropriate cycling interventions, leading to more consistent rehabilitation program results. Therefore, this study aimed to elucidate 3D kinematics of the lower extremity joints in musculoskeletally healthy and non-elite adults during cycling, determine kinematic differences depending on sex and age, and provide the literature on cycling rehabilitation.

Methods

This prospective study was approved by the institutional board of our hospital. Informed consent was obtained from all participants. All procedures were performed in accordance with relevant guidelines.

Participants who were over 18 years of age (i.e., legal adults) were competitively included in this study. Patients diagnosed with any musculoskeletal disease, those with a history of musculoskeletal trauma (including ligamentous injury and fracture), and those who were determined to have musculoskeletal deformities after the physician's physical examination were excluded from the study. To figure out the effects of age on kinematics, the participants were divided by the age of 10; group 1: <20 years old, group 2: 21–35 years old, group 3: 36–50 years old, and group 4: >50 years old. The physical examination was performed by a surgeon with 14 years of orthopedic experience.

Acquisition of kinematic data

Bicycle configuration can affect cycling performance. Thus, the positioning of each participant on the stationary cycle was standardized with the LeMond method, which is widely used and based on the empirical experience of a famous cyclist, Greg LeMond [27, 28]. The saddle height was measured from the center of the bottom bracket to the top of the seat along the seat tube. The saddle height was set at 88.3% of the distance between the highest point of one's inner thigh to the heel of one's foot, called an inseam (Fig. 1). This percentage is based on the average height of Westerners, and it is common to multiply the length by 0.855 for application to Asians. Therefore, the configuration of the saddle height was set at 85.5% of the inseam in this study.

A pedaling rate of 10–12 km/h was required throughout testing. To ensure that the rate was maintained, participants rode a bicycle ergometer (HealthWay, ROBUST S5, Korea) for several minutes before recording the kinematics. Data collection began when the participants were acquainted with the speed and kept a steady rate. We obtained 3D kinematic data using a Kestrel Digital System (Motion Analysis, Rohnert Park, CA, USA) equipped with 10 cameras. The Helen Hayes marker set was used to place markers on the top, back, and front of the head; both shoulders, elbows, and wrists; anterior superior iliac spine; thigh wand; lateral knee; shank wand; lateral ankle; heel; toe; and sacrum [29]. The movements of the pelvis, hip, knee, and ankle joints during cycling were evaluated in the sagittal, coronal, and transverse planes. The kinematic data were normalized to 0–100% of the cycling cycle. The right pedal at 0° was designated as 0%, and the right pedal after one 360° rotation (i.e., returned to 0°) was designated as 100%. The average value of three successive cycles was used for analysis.

Statistical analyses

The lower extremity kinematics for the participants' right side were used for analysis to avoid duplication of demographics [30]. The Kolmogorov-Smirnov test was used to verify the normality of the distribution of continuous variables. Descriptive statistics (i.e., mean ± standard deviation) were used to summarize the participants' demographic and kinematic data. Comparisons between male and female groups were conducted using the Mann-Whitney U test based on data characteristics. The Kruskal-Wallis test was used to compare the kinematics among age groups. K-fold cross-validation was used to evaluate machine-learning models with a limited data sample. All statistical analyses were conducted using SPSS version 20.0 (IBM Co., Chicago, IL), and a p-value < 0.05 was considered significant.

Results

Thirty-one participants were finally included in this study. The mean age at the time of examination was 35.0 ± 13.8 years (range, 18.2–68.1 years) (Table 1, Supplement 1). The mean saddle height was 68.0 ± 1.7 cm (range, 64.9–72.2 cm) for men and 64.8 ± 1.1 cm (range, 63.4–66.2 cm) for women (Table 1).

Table 1
Patient demographics.

Parameter	Value
No. subjects (Male/Female)	31 (23/8)
Age	35.0 ± 13.8 (18.2–68.1)
Height	172.1 ± 5.1 (162.9–185.0)
Male	174.1 ± 4.2 (166.8–185.0)
Female	166.5 ± 2.9 (162.9–170.0)
Inseam	78.5 ± 2.4 (74.2–84.5)
Male	79.5 ± 1.9 (75.9–84.5)
Female	75.8 ± 1.3 (74.2–77.4)
Saddle height	67.1 ± 2.1 (63.4–72.2)
Male	68.0 ± 1.7 (64.9–72.2)
Female	64.8 ± 1.1 (63.4–66.2)

Age, Height, Inseam, and Saddle height; mean ± standard deviation (range)

Age = decimal years

Saddle height = inseam x 0.855

The joint motions were observed in all three planes (Table 2, Fig. 2). During cycling, the pelvis moved very little in the sagittal plane. The ROMs were 43.9 ± 3.7° (hip), 75.2 ± 7.2° (knee), and 26.9 ± 10.5° (ankle). The coronal plane movement was observed in all joints; particularly, the knee ROM was 6.6 ± 2.7°, and the ankle ROM was 5.8 ± 3.2°. The transverse plane movement was also observed in all major lower extremity joints. Internal and external rotation occurred in the hip (11.6 ± 4.5°), ankle (10.3 ± 4.9°), and mainly in the knee joints (6.6 ± 2.7°).

Table 2
Sagittal, coronal, and transverse plane kinematics of lower extremity during cycling. Rt: Right, ROT: Rotation.

		Range of motion (•)		Maximum value (•)
Sagittal plane	Pelvis	1.6 ± 0.6 (0.7–3.6)	Posterior tilt	-15.0 ± 3.5 (-24.1 – -7.7)
			Anterior tilt	16.6 ± 3.6 (8.9–25.3)
	Hip	43.9 ± 3.7 (36.7–51.5)	Extension	-43.0 ± 5.1 (-54.4 – -34.5)
			Flexion	86.9 ± 4.3 (79.7–98.0)
	Knee	75.2 ± 7.2 (60.1–94.1)	Extension	-34.0 ± 9.8 (-57.2 – -14.7)
			Flexion	109.3 ± 3.9 (102.7–118.5)
	Ankle	26.9 ± 10.5 (10.8–47.0)	Dorsiflexion	7.6 ± 8.1 (-6.2–28.3)
			Plantar flexion	19.2 ± 7.6 (1.6–31.8)
Coronal plane	Pelvis	7.1 ± 2.5 (2.0–11.7)	Rt side up	3.5 ± 2.1 (-1.2–7.2)
			Rt side down	3.6 ± 2.4 (-1.1–7.8)
	Hip	5.0 ± 1.8 (1.6–10.8)	Adduction	10 ± 3.4 (5.9–21.8)
			Abduction	-5.1 ± 2.9 (-13.6 – -0.9)
	Knee	6.6 ± 2.7 (2.5–12.0)	Varus	1.6 ± 2.8 (-4.2–6.44)

		Range of motion (•)		Maximum value (•)
			Valgus	5.0 ± 2.2 (0.3–9.2)
	Ankle	5.8 ± 3.2 (2.1–14.2)	Inversion	1.5 ± 6.0 (-14.1–13.0)
			Eversion	4.3 ± 6.5 (-10.2–20.6)
Transverse plane	Pelvis	3.2 ± 1.9 (0.9–8.7)	Internal ROT	2.4 ± 3.1 (-4.2–8.8)
			External ROT	0.8 ± 3.3 (-4.3–12.5)
	Hip	11.6 ± 4.5 (3.3–23.8)	Internal ROT	6.3 ± 3.5 (-0.0–13.7)
			External ROT	5.3 ± 6.1 (-5.9–20.6)
	Knee	6.6 ± 2.7 (2.5–12.0)	Internal ROT	5.0 ± 2.2 (0.3–9.2)
			External ROT	1.6 ± 2.8 (-4.2–6.4)
	Ankle	10.3 ± 4.9 (3.9–22.0)	Internal ROT	4.4 ± 5.1 (-5.7–18.9)
			External ROT	6.0 ± 4.3 (-1.0–13.2)

The kinematic data of the pelvis, hip, knee, and ankle joints did not differ between the sexes ($p = 0.12$ to 0.95) or among ages ($p = 0.11$ to 0.96) in all anatomical planes. In k-fold cross-validation of the age groups, the area under the curve was between 0.475 and 0.610.

Discussion

Cycling is one of the most effective orthopedic rehabilitation methods to recover joint ROM with less weight load. Most studies have examined cycling in two dimensions, especially the sagittal plane [19, 31, 32], but recent studies have indicated that coronal and transverse movements also occur during cycling

[1, 10, 24]. Recently, 3D motion analysis is becoming critical for assessing full rehabilitation potential. Thus, this study evaluated the 3D lower limb kinematics of musculoskeletally healthy people during stationary cycling and aimed to provide guidance for a target recovery ROM for physical rehabilitation. This study showed that considerable movement occurs in the sagittal plane and also in the coronal and transverse planes. We also found that customizing the saddle height leads to constant joint kinematics.

The saddle position is often selected based on comfort. Improper positioning can lead to knee joint overuse injuries [2, 31, 33, 34] and inconsistent kinematics. Numerous methods have been proposed to determine the proper saddle height configuration [10]. We selected the LeMond method, as it is common, reliable [33], and simple to apply, which is important because most patients use public bicycles in clinics for rehabilitation purposes rather than private ones. We adjusted the saddle height to the length of each participant's inseam by multiplying the Asian-specific ratio. To our knowledge, this is the first study that considers the cycling rehabilitation environment based on race and individuals.

We found sagittal, coronal, and transverse movements in all joints during standardized ergometer cycling, enabling comprehensive rehabilitation guidance. When the sagittal joint ROMs obtained during ergometer cycling were compared with means of normal ROMs, the hip ROM was approximately 31%, the knee ROM was approximately 54%, and the ankle ROM was approximately 42% of normal [7, 35–40] (Fig. 3). The cycling kinematics of the lower limb joints were also compared to normal walking kinematics. The normal sagittal plane ROM during a human gait cycle is on average approximately 45° in the hip (ranging from 10° [extension] to 35° [flexion]), 55° in the knee (ranging from 5° [flexion] to 60° [flexion]), and 30° in the ankle (ranging from 15° [dorsiflexion] to 15° [plantarflexion]) [41, 42]. This indicates that the hip and knee joints were much more flexed during cycling and that the ankle joint motion was similar to that during walking. The overall joint motion during pedaling may not have an advantage over that during walking. However, the angle range where joint motion occurred during cycling was distinct from that during walking, suggesting that pedaling has effects that cannot be obtained by walking only. Thus, in terms of kinematics, cycling for musculoskeletal rehabilitation is highly recommended. Extra rehabilitative exercise is necessary to restore the ROM that is not covered by cycling. Lower limb kinematics are influenced by the saddle height [7, 10, 23]. Thus, the hip, knee, and ankle joint motions can be adjusted by changing the saddle height. For example, more plantar flexion could be created by increasing saddle height. Further investigation is needed to determine how cycling ROMs could be broadened for rehabilitation.

For the knee and ankle joints, significant internal and external rotation and coronal plane movements were observed. Cycling is recommended for individuals with knee disabilities because it puts less weight on the knee [4]. However, cycling considerably rotates the knee, which should be considered before starting bicycle rehabilitation for injuries adversely affected by rotational motion, such as meniscus and ankle ligament injuries. Understanding the 3D joint kinematics in healthy and normal individuals may help clinicians plan a target recovery ROM and issue guidance to patients.

This study attempted to recruit all adult patients of all ages for comparison according to sex and 10-year age groups. Pelvis, hip, knee, and ankle joint kinematics did not differ between sexes or among age groups, indicating that customizing the saddle height per individual results in constant kinematics regardless of sex and age. No studies have investigated the effects of sex and age on joint kinematics in the context of rehabilitation. Thus, these results provide a good reference for planning lower limb rehabilitation.

There were a few limitations in this study. First, there were a small number of participants. This was a pilot study in preparation for a large population study, and to overcome the small sample size, additional k-fold cross-validation was conducted. Second, the saddle height was set considering an empirical percentage for leg length (0.855 for Asians), and the bicycle configuration did not consider the handlebar position. Comparative research is needed to determine if other bicycle configurations change the effect on joint ROM or rehabilitation.

Conclusions

This study identified that stationary cycling generates movement in the sagittal, coronal, and transverse planes, enabling comprehensive lower limb rehabilitation. The findings can serve as a guide for setting the target kinematics during musculoskeletal rehabilitation with a stationary bicycle for individuals with orthopedic disabilities. The saddle height was adjusted for each participant, producing consistent joint motions. Given the limited number of studies on bicycle 3D movement for the general public (non-professional athletes), further work is warranted to determine a suitable ROM for cycling rehabilitation customizable to race and physical conditions.

Abbreviations

3D: Three-dimensional

ROM: Range of motion

ACL: Anterior cruciate ligament

Rt: Right

ROT: Rotation

Declarations

Ethics approval

Seoul National University Bundang Hospital Institutional Review Board in Seongnam, Korea approved the study protocol. (IRB No: B-2103/673-107). Informed consent was obtained from all participants.

Consent for publication

Not applicable.

Availability of data and materials

The datasets used and/or analyzed during this study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Not applicable.

Authors' contributions

All authors (HY, HK, TL, MSP, and SYL) in this manuscript made significant contributions to the study design. HY and SYL analyzed and interpreted the data, and wrote the article, and approved the final version of the manuscript. HK and MSP acquired and analyzed the data. TL helped to draft the manuscript and critically revised the manuscript. All authors have read and approved the final version of the manuscript.

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Figures

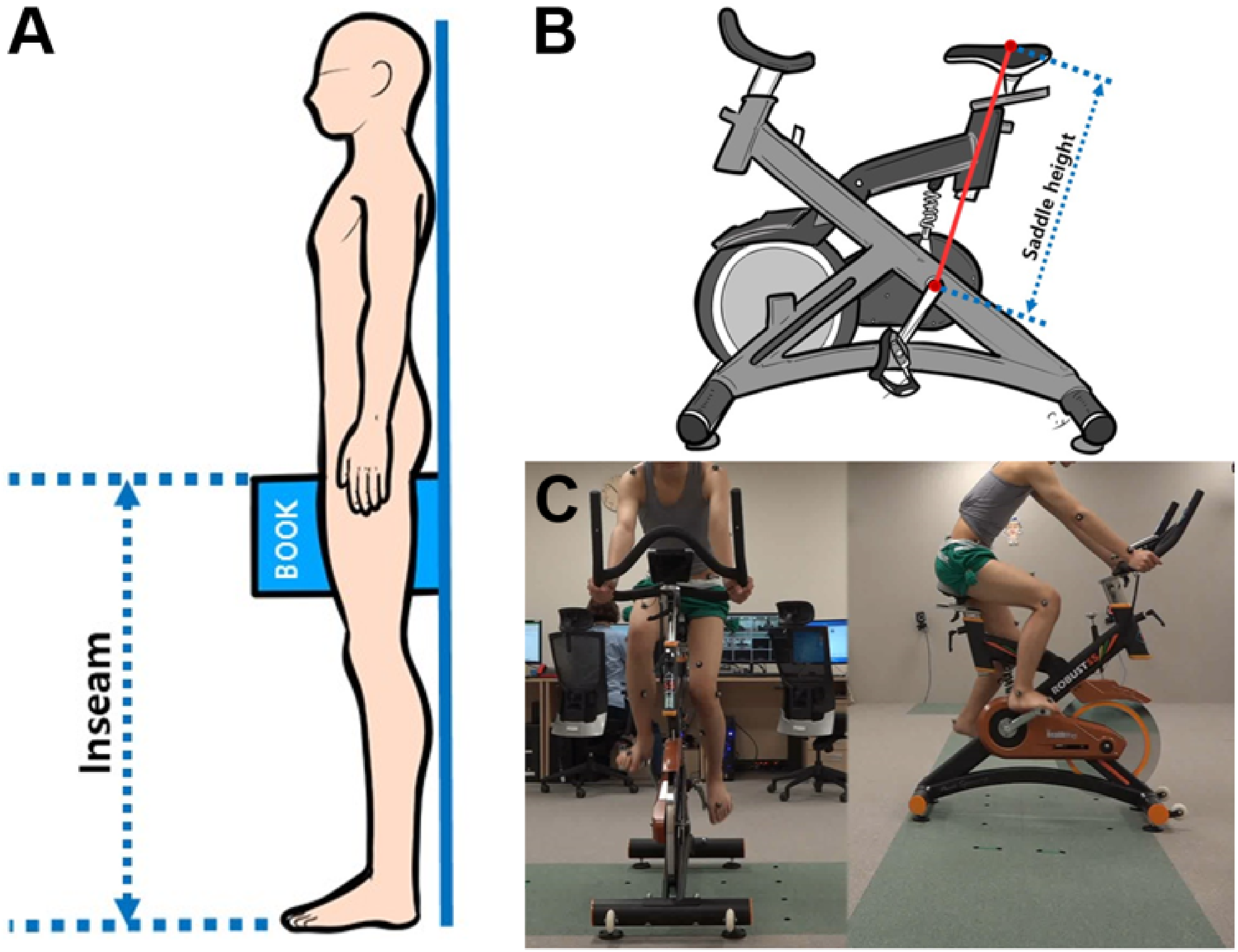

Figure 1

Measurements for the inseam (A) and saddle height (B), and the experimental setup showing a participant cycling on the stationary bike with the Helen Hayes marker set attached (C).

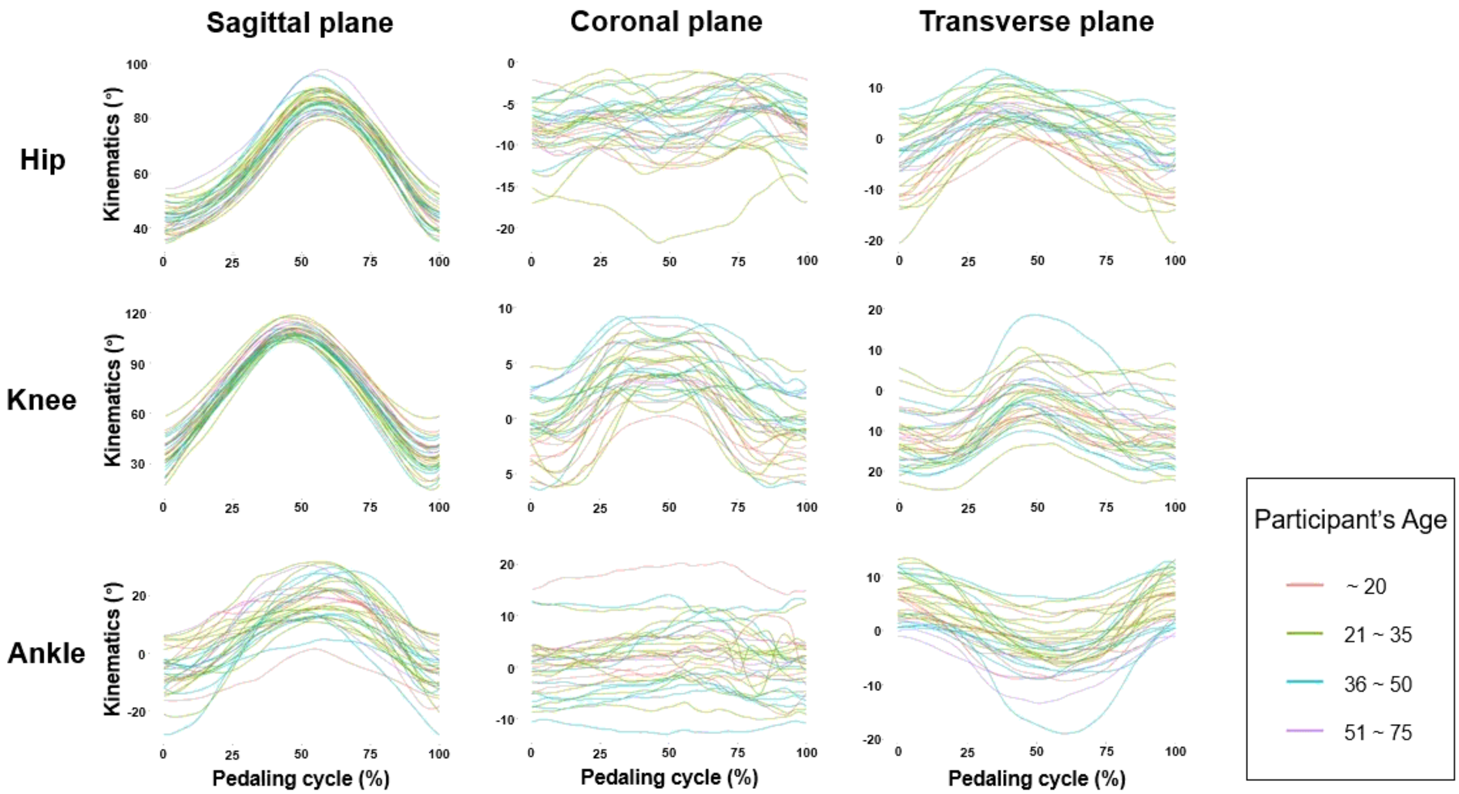

Figure 2

Hip, knee, and ankle joint angles for one complete revolution (0°–360°) of the bicycle crank for each participant's right leg in the sagittal, coronal, and transverse planes.

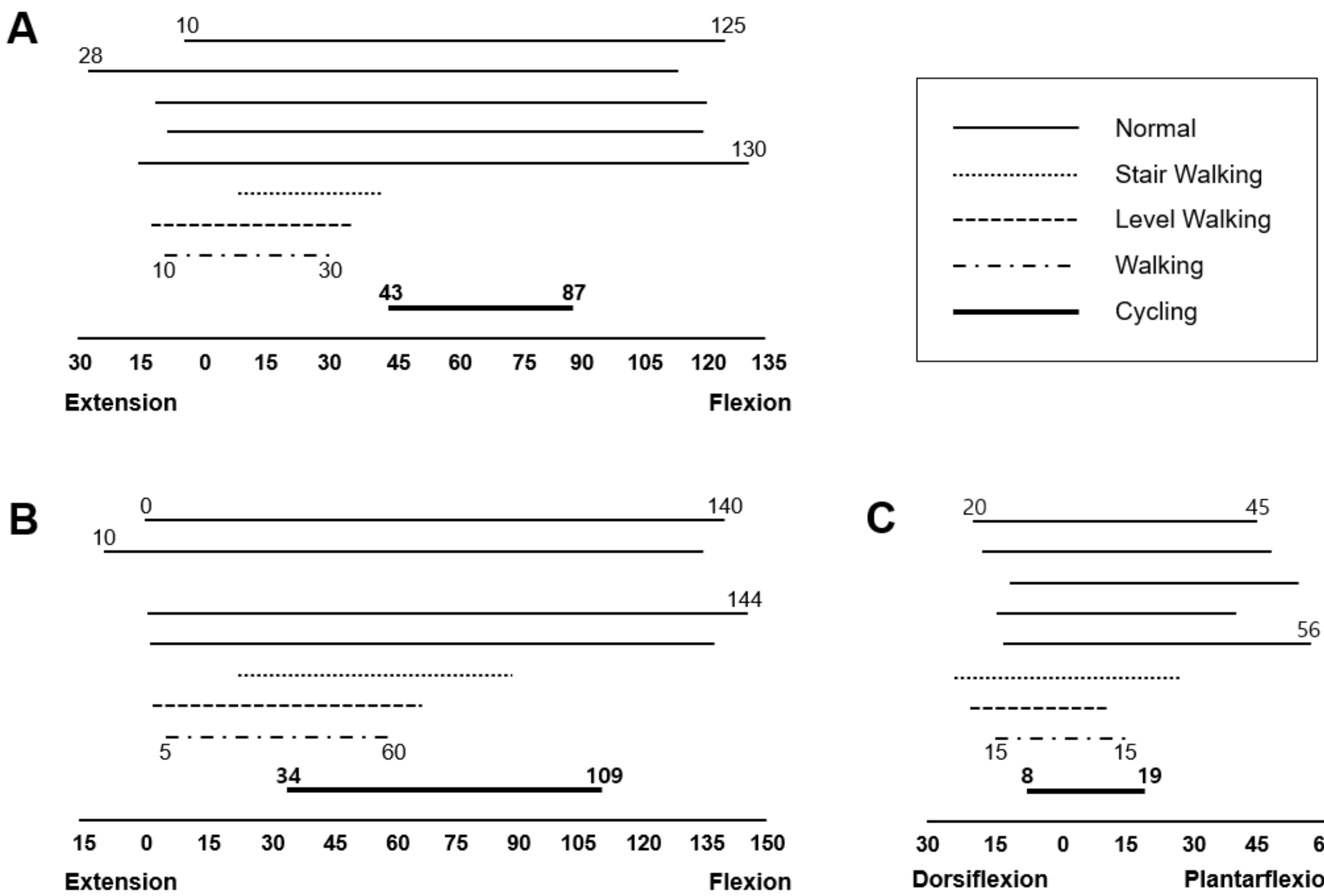

Figure 3

Comparisons among normal range of motions (ROM data reported by Kendall et al. [38, 39], Ericson et al. [7], the American Academy of Orthopaedic Surgeons [35], Boone et al. [36], Roaas et al. [37], and Soucie et al. [40]), and joint excursion during walking (Neumann [42] and Pietraszewski et al. [41]), stair or level walking (Ericson et al. [7]), and cycling (present study) of hip (A), knee (B), and ankle (C) joints. (degrees)

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