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Joint Motions of the Lower Limb during Ergometer Cycling

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The purpose of the study was to study the utilization of range of motion at the hip, knee, and ankle joints during exercise on a bicycle ergometer. Six healthy subjects biked at different workloads, pedaling rates, saddle heights, and pedal foot positions. The subjects were filmed in the sagittal plane with a cine-film camera at 60 frames/sec. The mean hip range of motion (ROM) during normal cycling was 38° ranging from 32–70° hip flexion. The mean knee ROM was 66° ranging from 46–112° knee flexion, and the ankle ROM was 24° ranging from 2° plantarflexion to 22° dorsiflexion. The hip, knee, and ankle joint motions were influenced by changes of the saddle height or pedal foot position. Different workloads had a small but statistically significant influence on the joint motions while different pedaling rates did not significantly change the lower limb joint motions. The range of motion utilized during cycling is approximately equal to, but more flexed compared to level walking and stair walking. The most effective way of increasing the ROM and obtaining more extension of the lower limb joints is to change the saddle height.

When cycling is utilized for exercise of patients with different needs it is valuable to know the range of motion required for various adjustments of the bicycle ergometer such as workload, speed, or saddle height or cycling technique (pedal foot position) used.

Cycling on a bicycle ergometer causes a high degree of muscular activity for the vastii muscles with a simultaneous training of the cardiovascular system.[8] The joint mobility and muscle strength might be improved by cycling in a safe and controlled manner that is suitable for the patient. Hence, the bicycle ergometer is often used in rehabilitation after hip,[31] knee,[5,6,15,17,24,34,35] and ankle[16,22] joint surgery. Cycling has also been prescribed for rehabilitation of patients with rheumatoid arthritis[28] or patellofemoral disorders.[20,29,32]

The mechanical load on different joint structures can be controlled by changes of the ergometer workload, pedaling rate, saddle height, or pedal foot position.[7,9-13] If desired and with a proper calibration of the bicycle ergometer, the mechanical load on the hip, knee, and ankle joints will be low in comparison with other weightbearing exercises or daily activities. Ericson et al. recently reported that the compressive hip,[13] knee,[11,12] and ankle[9] joint forces during normal ergometer cycling were equal to approximately 1 times the body weight (bw). In separate studies the tibiofemoral shear forces which primarily stress the anterior cruciate ligament are also very low at approximately 0.05 times bw.[11,17]

Houtz and Fischer[18] studied the muscle action and joint excursion during exercise on a stationary bicycle. They stated that the bicycle is a useful therapeutic device for increasing the range of motion (ROM) in the hip, knee, and ankle joints within certain limits. They also claimed that it is possible to develop approximately 20–40° of motion in the hip, from 40 to 65° in the knee, and complete range of motion in the ankle.[18] Nordeen and Cavanagh[26] developed a model for simulation of lower limb kinematics during cycling. Nordeen-Snyder[27] studied the effect of bicycle seat height variation (95, 100, and 105% trochanteric height) upon lower limb kinematics. She found that the ROM at the hip does not change, while the major adaptions to saddle height increases occur at the knee and in ankle plantarflexion. The hip, knee,

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and ankle joints demonstrated greater extension with an increase in saddle height. Faria and Cavanagh[14] reported a small but significant increase in ankle range of motion when increasing the workloads. McLeod and Blackburn[24] studied the location of the tibial plateau and the tibial angle during cycling at different seat heights and pedal positions. Based upon kinematic and EMG data they discussed the biomechanics of knee rehabilitation with cycling. Suzuki et al.[33] found that the angular movement of the hip joint tends to become smaller as speed increases while the range of movement of the knee joint remains comparatively constant. Hubley et al.[19] recently found that static stretching and cycling were equally effective for increasing hip range of motion and retaining the increase for a 15-min period in a controlled environment, independent of activity.

The general purpose of this study was to determine the joint motions in the lower limb during ergometer cycling with changes of seat height, pedaling rate, workload, and foot position. The range of motion utilized during exercise on the bicycle ergometer was also compared to the total normal range of motion[1,4,30] and the range of motion utilized during walking[21,23,25] or stair walking.[2] The present kinematic analysis of cycling may, together with studies on the joint load[7,9–13] and the lower limb muscular activity[8], provide a better knowledge and understanding for the use of the bicycle ergometer in rehabilitation medicine.

The following specific questions were analyzed:

1) What is the range of the hip, knee, and ankle joint motions during standardized ergometer cycling?

2) How do the hip, knee, and ankle joint motions vary with workload, pedaling rate, saddle height, and foot pedal position?

3) What is the range of joint motion during cycling compared to normal range of motion and to the range of motion utilized during normal gait or stair walking?

MATERIALS AND METHODS

Six healthy subjects, all male aged between 20 and 31 years of age (mean = 25.3 years), participated in the study. Their average height and weight were 1.80 m (SD = 0.06) and 71.3 kg (SD = 5.0), respectively. The subjects were students with ordinary daily and recreational cycling experience. None of the subjects suffered from locomotor pain nor had previously been subjected to any joint surgery or had any periods of sick leave caused by disorders of the musculoskeletal system.

A weight braked bicycle ergometer (Cardionics with weight brakes, Cardionics, Stockholm, Sweden) was used. The following variables were studied:

1) Workload: zero, 120, and 240 Watt (W).

2) Pedaling rate: 40, 60, 80, and 100 revolutions per minute (rpm).

3) Saddle height: "low, mid, and high" determined as a percentage (102, 113, 120%) of the distance between the ischial tuberosity and the medial malleolus measured on each subject. The saddle height was measured as the greatest distance from saddle surface to the center of the upper pedal surface in a straight line along saddle pillar and crank.

4) Foot position: one anterior and one posterior foot position were used. The anterior was defined as the position when the center of the pedal was in contact with the head of the second metatarsal (ball of foot), and the posterior foot position (instep) approximately 10 cm posterior to the anterior foot position.

When one of the four variables was changed and studied, the other three were held constant with one major exception (workload). When the pedaling rate was changed (40, 60, 80, and 100 rpm) a braking weight of 2 kg was used and hence the workload was 80, 120, 160, and 200 W, respectively, at the four pedaling rates studied. The different workloads were regulated by adding weights (zero, 2, and 4 kg) to the weight braked bicycle ergometer. The adjustment of 120 W, 60 rpm, mid-saddle height, and anterior foot position was defined as "standardized ergometer cycling."[9] In order to eliminate systemic effects of fatigue, the internal sequence of the nine different test situations was randomized. The saddle heights determined as described above were adjusted to the nearest fixed position with a maximum error of ±1.5 cm. The handlebars were kept level with the saddle. The cyclist's trunk was inclined forward 20–30° from the vertical. All subjects were allowed to warm up and become accustomed to cycling on the specially instrumented bicycle ergometer. They practiced at all the different workloads, pedaling rates, saddle heights, and foot positions included in the study before the experimental recordings started.

All measurements were performed on the left lower limb. Time was registered using an instrument specifically designed for this study. The time indication panel housed a light emitting diode display which produced a bar representation of time in units down to 1 msec. The different test situations were filmed using a 16 mm cine-film camera (Paillard Bolex, 60 frames/sec), perpendicular to the sagittal plane of the subject at a distance of 3.5 m. As landmarks for the bilateral hip, knee, and ankle joint-axes, dye marks were placed on the skin 1 cm anterior and superior of the tip of the greater tubercle of the femur, at the center of the lateral epicondyle of the femur, and at the tip of the lateral malleolus. Time, as indicated by the time indication panel, was visible on each film frame.

The subjects cycled for 30 sec on each test occasion before the measurements were performed. A metronome was used to enable each subject to find and keep the correct pedaling rate. The subjects were filmed during 5 sec intervals. Three of the five revolutions registered were selected and analyzed throughout the complete pedal revolution. The film was analyzed with a projector (Analector ANL4), which made it possible to "freeze" the film and trace the picture. Pictures were traced from the cine-film at intervals of approximately 15° crank angle. The position for the hip, knee, and ankle joint axes and crank angle were then determined using the traced pictures (Fig. 1). The joint angles were measured from the drawn pictures. The test/retest error in joint angle measurements from the cine-film was determined to ±1°.

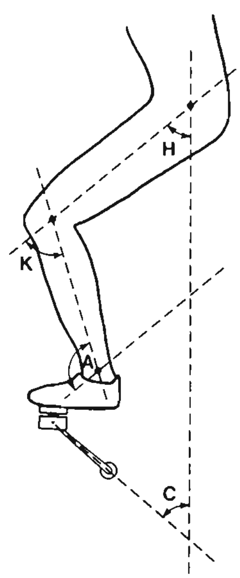

Fig. 1. *Hip (H), knee (K), and ankle (A) joint angles. Zero and 360° crank angle (C) corresponds to the position when the pedal is in its top position and 180° to the pedal bottom position.*

The significance of changes of hip, knee, and ankle joint motion caused by changes of workload, pedaling rate, saddle height, and pedal foot position was statistically analyzed by means of one-factor, repeated measures analysis of variance (ANOVA). The level of significance was consistently chosen to be $p < 0.05$.

RESULTS

The mean hip, knee, and ankle joint motions during "standardized ergometer cycling" are shown in Figure 2. The range of motion (ROM), maximum joint flexion, and extension are also given in Table 1.

Saddle Height and Foot Position

The variation of hip joint motion with different saddle heights and foot positions is shown in Figure 3. Raising the saddle from low to high position at the anterior foot position caused a significant increase in hip extension of 19° and a simultaneous decrease in hip flexion of 16°. The magnitude of the ROM was not significantly changed. At the midsaddle position, cycling with

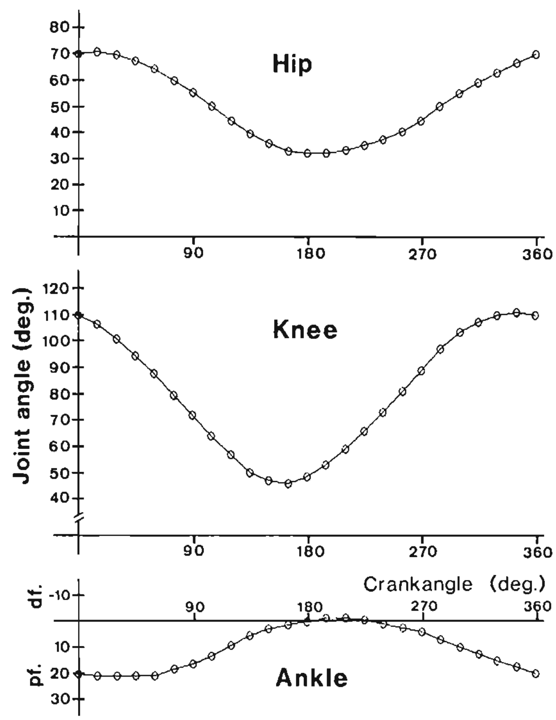

Fig. 2. *Mean hip, knee, and ankle joint motions (deg., degrees) during ergometer cycling at 120 W, 60 rpm, midsaddle height, and anterior foot position. (pf., plantarflexion; df., dorsiflexion).*

TABLE 1

The mean ROM utilized at the hip, knee, and ankle joints during standardized ergometer cycling (present study) compared to the normal range of motion reported by the American Academy of Orthopaedic Surgeons (AAOS),[1] Boone and Azen (B & A),[4] Roaas and Andersson (R & A).[30] ext, extension; flex, flexion

	Hip			Knee			Ankle		
	flex	ext	ROM	flex	ext	ROM	flex	ext	ROM
AAOS	113	−28*	141	134	−10*	144	48	−18*	66
B & A	121	−12*	133	141		141	54	−12*	66
R & A	120	−9*	129	144	2	142	40	−15*	55
Cycling (Present study)	70	32	38	112	46	66	22	−2*	24

* Negative values in joint extension columns indicates that the particular joint is not extended, but still flexed as much as the depicted value indicates.

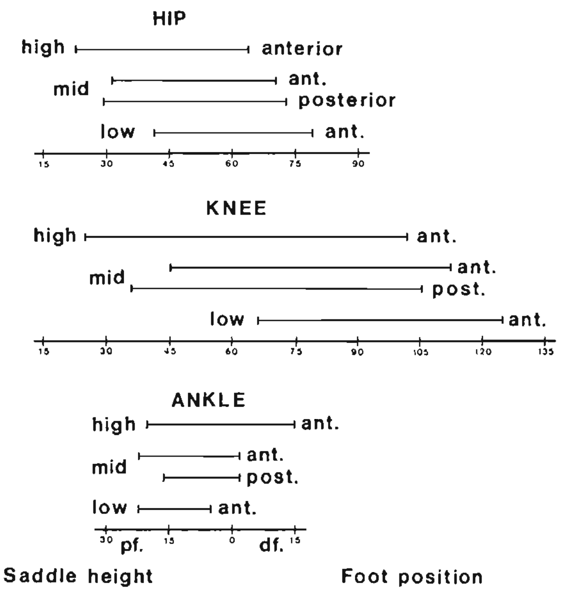

Fig. 3. *Lower limb joint excursion during ergometer cycling at different saddle heights (low, mid, and high)and foot positions (ant., anterior; post., posterior). pf., plantarflexion; df., dorsiflexion; deg., degrees.*

the ball of the foot instead of the instep caused a small but statistically significant decrease of the hip ROM of 7° and a decrease in hip extension of 2°. Hip flexion was not significantly changed with change of the foot position.

The variation of the knee joint motion with different saddle heights, and foot positions is shown in Figure 3. Raising the saddle from low to high position at the anterior foot position caused a significant increase in the knee ROM of 15°. Knee extension increased 41° and knee flexion decreased 22°. At the midsaddle height, cycling with the anterior foot position instead of the posterior caused a significant decrease in knee ROM of 3°, increase in knee flexion of 7°, and decrease in knee extension of 10°.

The variation of ankle joint motion with different saddle heights and foot positions is shown in Figure 3. Raising the saddle from low to high position at the anterior foot position caused an increase in ankle ROM of 18° and a plantarflexion increase of 20°. The ankle dorsiflexion was not significantly influenced by different saddle heights. The anterior foot position compared to the posterior at the midsaddle height caused an increase in ankle ROM of 5° and in ankle dorsiflexion of 5°. The ankle plantarflexion was not significantly changed with different foot positions.

Workload

The workload increase from 0–240 watt (W) caused slight but still statistically significant differences in joint motions of the three joints investigated. The change of mean maximum hip joint flexion angle when increasing the workload from 0–240 W was small (from 71–69°) but statistically significant and the mean maximum hip extension angle changed from 33–30°. The hip ROM was not significantly influenced by changes of the ergometer workload. The mean maximum knee joint extension angle significantly decreased from 49–42° but maximum knee flexion and ROM were not significantly influenced by changes of the workload. The dorsiflexion angle significantly increased from 17–26° while ankle plantarflexion was not significantly altered with a change of the ergometer workload. The ankle ROM increased from 21–29°.

Pedaling Rate

An increase of the pedaling rate from 40–100 rpm did not significantly change the motions of any of the three joints studied.

DISCUSSION

The joint motions obtained during standardized ergometer cycling might be compared with the normal range of motion of the hip, knee, and ankle joints[1,4,30] or the lower limb joint motions obtained during other activities such as level walking[21,23,25] or stair walking.[2]

The normal range of motion has been investigated by different authors (Table 1). A comparison of these studies indicated that the hip ROM utilized during normal ergometer cycling measured approximately 28% of the normal hip range of motion (Table 1). The knee ROM during cycling measured about 45% of the normal range of motion, and the ankle ROM about 40%.

In Figure 4 the lower limb kinematics during level walking and stair walking studied by others have been compared to the results of the present study.[2,21,23,25] During cycling the magnitudes of the hip, knee, and ankle joint ROM were similar to the ROM utilized during normal gait. However, the hip and knee joints were much more flexed and the ankle joint more dorsiflexed during cycling compared to walking. With a reasonable and not extreme increase of the saddle height the joint motions obtained during cycling will be more equal to the one utilized during level walking. The use of the posterior foot position will also increase the magnitude of hip and knee joint extension.

In the present study statistically significant changes of joint motions as small as 2° were found. However, such small differences in joint motion have no clinical relevancy. The only way to obtain changes that might increase the patients

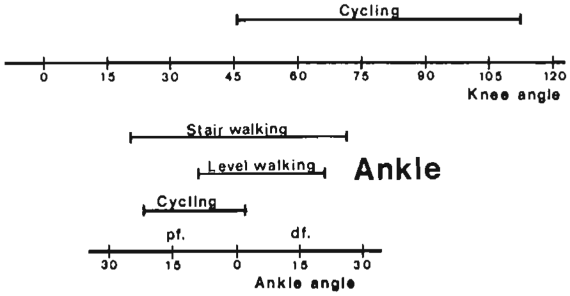

Fig. 4. *Comparison between the joint excursion during level walking (means of data reported by Murray et al.,[25] Lamoreux,[21] and Mann et al.[23]), stair climbing (Andriachii et al.[2]), and ergometer cycling (present study). (deg., degrees).*

range of motion was to change the saddle height or pedal foot position.

The major change in hip and knee joint motions was obtained when changing the saddle height (Fig. 3). The increased knee and ankle range of motion at higher saddle positions (Fig. 3), are caused by the increased distance between the hip joint and the pedal when raising the saddle. To reach the bottom position of the pedal the subject must extend the limb more, which in the knee and ankle was seen as an increased knee extension and plantarflexion, respectively.

Cycling at the posterior foot position increased the hip and knee range of motion and also increased the hip and knee extension. These increases are probably because the "effective" limb length is shorter at the instep foot position. This "shortness" demands more hip and knee extension seen as an increased hip and knee joint range of motion.

The small but statistically significant increase in ankle range of motion when increasing the workloads, also discussed by Faria and Cavanagh,[14] are almost certainly to be explained by the increase in ankle loading.[9] The increased dorsiflexing ankle load moment causes an increase in the dorsiflexion and the forces acting on the plantarflexor muscles.

Suzuki et al.[33] studied the limb kinematics during cycling at different pedaling rates (between 12–198 rpm) and found a decreased range of angular movement at the hip with increasing speed while the knee motion remained relatively constant. In the present study no statistically significant changes of the limb motions with increased speed were found. The greater range of speeds investigated by Suzuki et al.[33] (12–198 rpm) compared to the present study (40–100 rpm) may explain the differences. However, the pedaling rates investigated in the present study (40–100 rpm) are closer to the speeds normally used in recreational cycling, exercise tests, and in medical rehabilitation.

For purposes of training and increasing ROM in the lower limb joints, cycling might be favorable as the exercising patient is able to make a great number of repetitions in a short time and at a low mechanical joint load. Recently, two studies have shown that the load on the anterior cruciate ligament is very low during cycling exercises.[11,17] Ericson et al.[8] have also reported that the vastii muscles are very active during cycling. In the early postsurgical rehabilitation of patients with injuries to the anterior cruciate ligament it might be desirable to avoid knee angles less than 45° because of an increased ligamentous strain.[3] The present study revealed that cycling at mid or low saddle heights with the anterior foot position does not require knee angles greater than 45°. Hence, because of the low strain forces induced at the anterior cruciate ligament, cycling might be an exercise of choice for those patients. Furthermore, the mechanical load and joint motion can be controlled and changed to the desired magnitude.

CONCLUSION

The magnitude of range of motion utilized at the hip, knee, and ankle joints during exercise on a bicycle ergometer is approximately equal to, but often more flexed compared to normal level walking and stair walking. With an appropriate adjustment of the saddle height or foot position a controlled range of motion can be obtained.

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