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Effects of Saddle Height, Pedaling Cadence, and Workload on Joint Kinetics and Kinematics During Cycling

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Context: It is not clear how noncyclists control joint power and kinematics in different mechanical setups (saddle height, workload, and pedaling cadence). Joint mechanical work contribution and kinematics analysis could improve our comprehension of the coordinative pattern of noncyclists and provide evidence for bicycle setup to prevent injury. ***Objective:*** To compare joint mechanical work distribution and kinematics at different saddle heights, workloads, and pedaling cadences. ***Design:*** Quantitative experimental research based on repeated measures. ***Setting:*** Research laboratory. ***Patients:*** 9 healthy male participants 22 to 36 years old without competitive cycling experience. ***Intervention:*** Cycling on an ergometer in the following setups: 3 saddle heights (reference, 100% of trochanteric height; high, + 3 cm; and low, – 3 cm), 2 pedaling cadences (40 and 70 rpm), and 3 workloads (0, 5, and 10 N of braking force). ***Main Outcome Measures:*** Joint kinematics, joint mechanical work, and mechanical work contribution of the joints. ***Results:*** There was an increased contribution of the ankle joint ($P = .04$) to the total mechanical work with increasing saddle height (from low to high) and pedaling cadence (from 40 to 70 rpm, $P < .01$). Knee work contribution increased when saddle height was changed from high to low ($P < .01$). Ankle-, knee-, and hip-joint kinematics were affected by saddle height changes ($P < .01$). ***Conclusions:*** At the high saddle position it could be inferred that the ankle joint compensated for the reduced knee-joint work contribution, which was probably effective for minimizing soft-tissue damage in the knee joint (eg, anterior cruciate ligament and patellofemoral cartilage). The increase in ankle work contribution and changes in joint kinematics associated with changes in pedaling cadence have been suggested to indicate poor pedaling-movement skill.

Keywords: inverse dynamics, injury prevention, joint mechanics, bicycle ergometry, knee joint, biomechanics

For rehabilitation, it has been reported that cycling has the advantage of minimizing stress on the joints.[1,2] Ericson et al[3] indicated that the moments at the hip and knee joints during cycling are smaller than with other exercises (ie, walking),

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and Fleming et al[4] noted that high-impact forces are prevented during stationary cycling, with low strain imposed to the anterior cruciate ligament. However, recreational bikes and stationary cycle ergometers used for rehabilitation have been set up based on empirical knowledge without scientific guidance.[5]

The control of joint mechanical work and kinematics has been described for performance,[6] but there is no evidence for this variable for rehabilitation cycling. McLeod and Blackburn[2] introduced the use of stationary cycle ergometers for knee rehabilitation only based on joint kinematics, and Neptune and Kautz[7] and Bressel[8] measured joint load only during steady-state cycling. In this regard, workload and pedaling cadence and their effects on joint kinematics, joint mechanical work, and mechanical work contribution of the joints have not been fully addressed.

For low workload, only Ericson[9] focused on mechanical work contribution of the joints, reporting no significant effects of a variation from zero to 120 W. Pedaling cadence has been described to increase knee- and reduce hip-joint contribution to total mechanical work.[10] However, Hoshikawa et al[11] observed the opposite, and Ericson[9] reported no effects of pedaling cadence on joint mechanical work distribution. Joint kinematics have been affected by pedaling cadence[12] without evidence of low workload manipulation.

In spite of previous reporting for workload and pedaling cadence, the control of joint mechanical work has been described to be unaffected by saddle height manipulation.[13] However, pedaling technique,[9,14] muscle activity,[15] and joint kinematics[16] have been reported to be affected by saddle-height changes. Gonzalez and Hull[17] also observed saddle height's effects on hip- and knee-joint moments. Rugg and Gregor[18] and Sanderson and Amoroso[19] introduced kinematics measurement for the analysis of muscle length, suggesting that saddle height would also affect the muscle force–length relationship.

Most of these results focused on cycling for performance, which did not fully address how noncyclists control joint power and kinematics in different mechanical setups (saddle height, workload, and pedaling cadence). The measurement of joint mechanical work distribution and kinematics might improve our comprehension of the coordinative pattern of noncyclists during rehabilitation cycling and provide evidence for manipulating bicycle setup to prevent injury.

Hence, the aim of the current study was to compare mechanical work contribution of the joints and kinematics of noncyclists at different saddle heights, pedaling cadences, and low workloads. Our main hypothesis was that noncyclists would adapt the control of joint mechanical work and kinematics to sustain performance when the aforementioned mechanical setups were changed.

Methods

Design

This study used a quantitative experimental design based on repeated measures of joint mechanical work distribution and kinematics of participants during a single evaluation session.

Participants

Nine healthy male subjects between 22 and 36 years of age without lower limb joint injuries or competitive experience in cycling volunteered to participate in the study. All participants signed an informed-consent form in agreement with the university's Committee on Ethics in Research With Humans in accordance with the Declaration of Helsinki.

Procedures

Body weight and the height of the great trochanter were measured at the beginning of an evaluation session as reported by Nordeen Snyder.[16] A Monark bicycle ergometer (GIH, Monark, Stockholm, Sweden) with weight brakes was employed with the following setups: 3 saddle heights (reference, 100% of trochanteric height; high, + 3 cm; and low, – 3 cm), 2 pedaling cadences (40 and 70 rpm), and 3 workloads (0, 5, and 10 N of braking force). These variables were evaluated during 1 session in random order, resulting in 18 trials combining saddle height, pedaling cadence, and workload. In order to reduce resting time between trials, the first adjustment conducted was the saddle height, followed by pedaling cadence and finally the workload. Figure 1 outlines the experimental protocol.

For changes in saddle height, the subjects were asked to stand up from the saddle and lay their weight on the handlebars and on both pedals for 30 seconds. After each change in pedaling cadence and workload, 1 minute of practice was allowed for subjects to adapt to the intended pedaling cadence.

Normal and tangential components of force applied to the pedal were recorded from an instrumented 2-D right pedal.[20] Force data were acquired using a WINDAQ acquisition system (Dataq Instruments, Akron, OH) at ×1000 gain. The data were digitized with a resolution of 16 bits using an analog-to-digital converter (DI720, Dataq Instruments, USA) and recorded at a sampling frequency of 540 Hz. Each trial lasted 30 seconds. Sagittal-kinematics variables were acquired from cyclists' right lower limb by a single camera (Peak HSC-180, Peak Motus, Peak Performance Technologies, Englewood, CO) perpendicular to the movement plane and 3.5 m away from the subject. The images were acquired at 180-Hz sampling frequency.[21] Reflective markers were attached to the right lower limb of the cyclists over the anatomical reference points of the greater trochanter, lateral femoral condyle, and lateral malleolus; the pedal spindle; an anterior and posterior stick attached to the pedal; and at the crank spindle.[6] This stick was 25 cm long and was used to measure the pedal angle relative to horizontal. Pedal forces and kinematics were acquired simultaneously during 10 complete pedal revolutions and synchronized by an electronic trigger. Pedal forces and kinematic data were smoothed by a Butterworth low-pass digital filter with cutoff frequencies of 10 Hz and 4 Hz, respectively.[6] Joint angles were defined as depicted in Figure 2.

Linear and angular velocities and accelerations were computed from smoothed data. Pedal angle in the global coordinate system was used to convert the forces on the pedal reference system to forces on the global reference system by means of trigonometric procedures.[6] The right lower limb was modeled as a 3-segment (thigh, shank, and foot-pedal) rigid-body system with the segments' mass and center of mass estimated.[22] Conventional inverse dynamics was used to calculate the net joint moments and resultant forces at the hip, knee, and ankle.[6] Joint power was calculated by the product of the net joint moments and angular velocity, and net joint mechanical work was calculated by integrating the joint power with respect to time.[10,11] The relative contributions of the ankle, knee, and hip joint were calculated as the percentage of total joint mechanical work (TMW) at 3 joints.[11] All

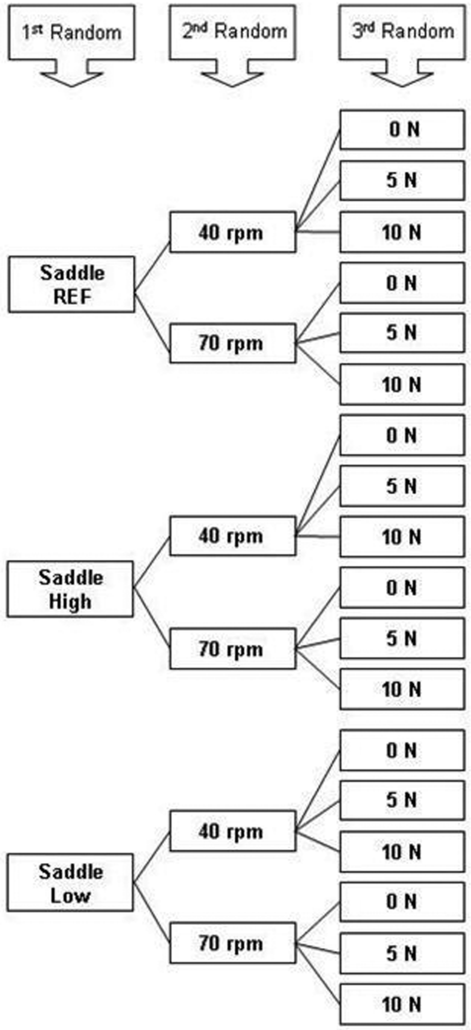

Figure 1 — Experimental-protocol representation indicating each randomized set of changes: first the saddle height, second pedaling cadence, and third workload. Abbreviations: REF, reference height.

data analyses were conducted following proper codes developed using software Matlab 7.3 (Matlab, Mathworks Inc, USA).

Statistical Analysis

Descriptive statistics were used to report the mean and standard error (SE), with data-normality distribution evaluated by Shapiro–Wilks test. A 3-way repeated-measures ANOVA (3 saddle heights × 2 pedaling cadences × 3 workloads) was

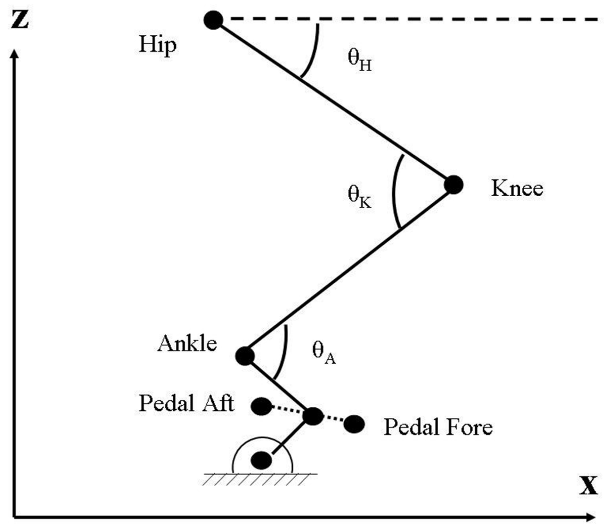

Figure 2 — Schematic illustration of angle definitions for kinematic analysis. Angle definitions: θH, hip angle; θK, knee angle; θA, ankle angle.

employed. The variables tested were the TMW; hip-, knee-, and ankle-joint mechanical work; relative contribution of each joint to the TMW (mechanical work contribution of the joints); and joint kinematics (mean angle and range of motion [ROM]). Main effects were measured by Bonferroni post hoc test with statistical significance for type I set at 5% and for type II ($1 - \beta$) at 80%. We used SPSS 12.0 software (SPSS Inc, Chicago, IL) for all statistical analysis.

Results

Significant differences were observed for total mechanical work of the lower limb joint (TMW) for workload changes ($F_{1.09,8.71} = 39.37$, $P < .01$, $1 - \beta = 1$), which resulted in 24 ± 2.4, 28 ± 3.2, and 36 ± 3.9 J, for 0, 5, and 10 N, respectively. A significant increase in TMW was observed for 5 N in relation to 0 N ($P < .01$) and for 10 N in relation to 0 N ($P < .01$) and 5 N ($P < .01$). Neither saddle height ($F_{2,16} = 1.243$, $P = .315$, $1 - \beta = .23$) nor pedaling cadence ($F_{1,8} = 3.349$, $P = .105$, $1 - \beta = .36$) affected TMW.

Figure 3 presents joint-power average data at each lower limb joint for 1 subject at reference, high, and low saddle heights at 70 rpm and 10 N of workload.

Joint mechanical work was computed, and the effects of saddle height, pedaling cadence, and workload in ankle, knee, and hip mechanical work are depicted in Figure 4.

There was a significant increase in ankle ($F_{2,16} = 35.109$, $P < .01$, $1 - \beta = 1$), knee ($F_{1.108,8.637} = 62.552$, $P < .01$, $1 - \beta = 1$), and hip mechanical work ($F_{1.108,8.643} = 19.80$, $P < .01$, $1 - \beta = .98$) with increased workload. There was no effect of saddle height or pedaling cadence on ankle- ($F_{2,16} = 3.354$, $P = .06$, $1 - \beta = .55$, and $F_{1,8} = 0.333$, $P = .58$, $1 - \beta = .08$, respectively), knee- ($F_{2,16} = 2.799$, $P = .09$, $1 - \beta = .47$,

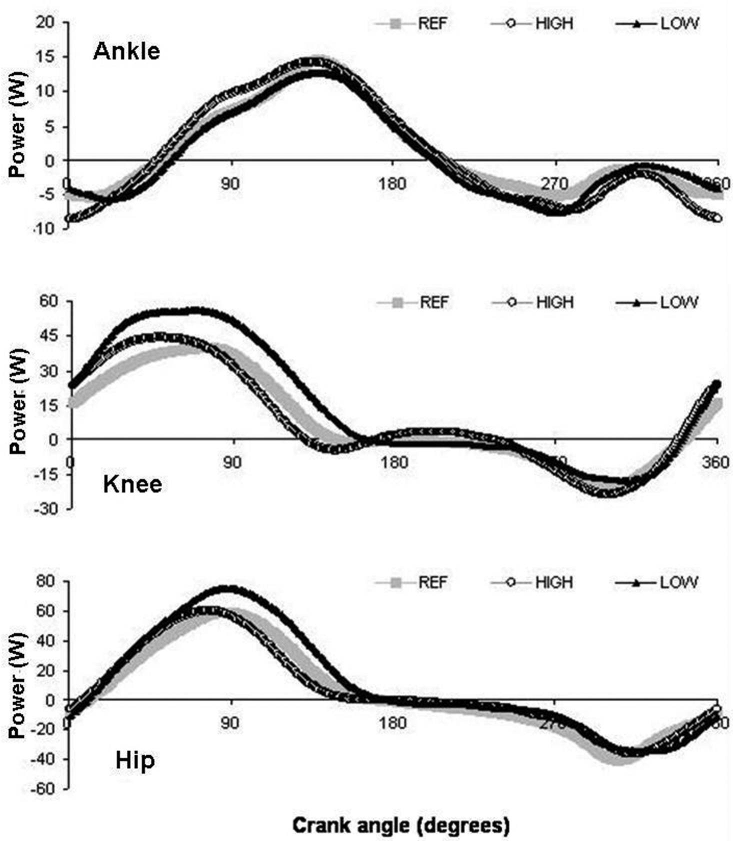

Figure 3 — Representative data on joint power from 1 subject at reference (REF), high, and low saddle heights at 70 rpm and 10 N of workload. Negative values indicate mechanical energy absorption at the joint.

and $F_{1,8} = 3.244$, $P = .11$, $1 - \beta = .35$, respectively), or hip-joint mechanical work ($F_{2,16} = 0.462$, $P = .64$, $1 - \beta = .11$, and $F_{1,8} = 3.456$, $P = .10$, $1 - \beta = .37$, respectively).

The effects of saddle height, pedaling cadence, and workload on ankle, knee, and hip contribution to TMW are depicted in Figure 5.

Ankle work contribution significantly increased ($F_{2,16} = 4.117$, $P = .04$, $1 - \beta = .64$) at higher saddle height (high × low), as with increased pedaling cadence ($F_{1,8} = 11.549$, $P < .01$, $1 - \beta = .84$). Knee work ratio was significantly different between low and high saddle heights ($F_{2,16} = 7.134$, $P < .01$, $1 - \beta = .88$) and increased with increasing workload ($F_{2,16} = 87.459$, $P < .01$, $1 - \beta = 1$). There was a decreased hip ratio with the increase in workload ($F_{1.152,9.212} = 63.621$, $P < .01$, $1 - \beta = 1$).

Figure 6 depicts average angle data at each lower limb joint for 1 subject at reference, high, and low saddle heights at 70 rpm and 10 N of workload.

Joint kinematics were compared with changing saddle height, pedaling cadence, and workload by means of the mean value and the ROM of each joint angle. These results are presented in Figure 7.

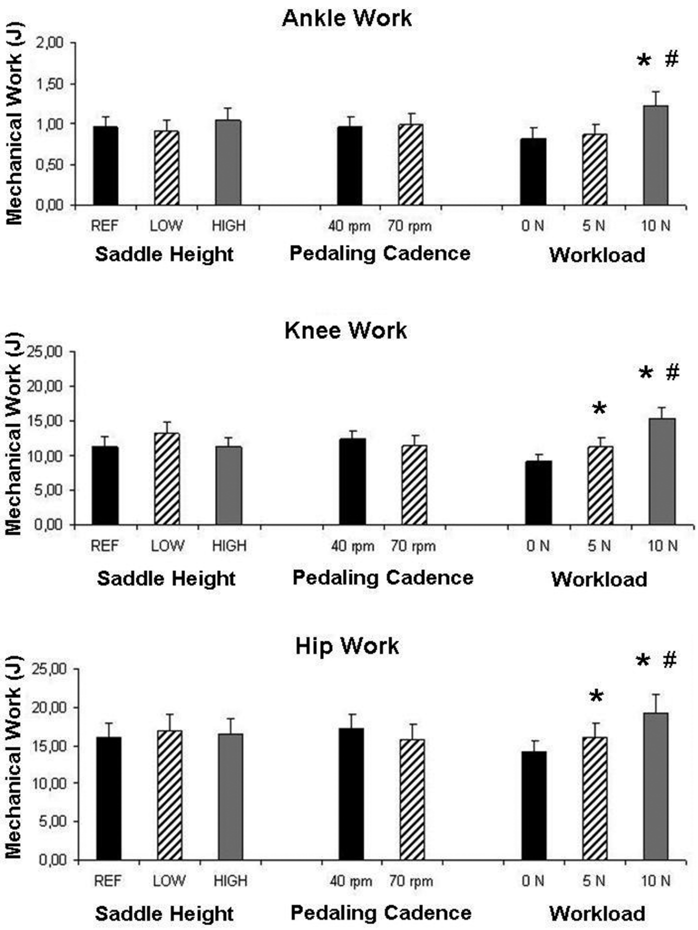

Figure 4 — Mean (± SE) results of joint mechanical work computed at the ankle, knee, and hip joints in the 3 saddle heights (reference [REF], high, and low), 2 pedaling cadences (40 and 70 rpm), and 3 workloads (0, 5, and 10 N). *Significant difference related to 0 N ($P < .05$). #Significant difference related to 5 N ($P < .05$).

There was a significant increase in ankle mean angle with increasing pedaling cadence ($F_{1,8} = 18.415$, $P < .01$, $1 - \beta = .96$), whereas ankle ROM increased with the decrease in saddle height ($F_{2,16} = 22.251$, $P < .01$, $1 - \beta = 1$) and decreased at higher pedaling cadence ($F_{1,8} = 5.722$, $P = .04$, $1 - \beta = .56$). No effects were observed for workload changes in angle kinematics. Knee mean angle increased with decreased saddle height ($F_{2,16} = 42.051$, $P < .01$, $1 - \beta = 1$), with the opposite result for knee ROM ($F_{2,16} = 6.806$, $P < .01$, $1 - \beta = .86$). For hip mean angle ($F_{2,16} = 39.172$, $P < .01$, $1 - \beta = 1$) and ROM ($F_{2,16} = 7.251$, $P < .01$, $1 - \beta = .88$), the same pattern of knee-joint kinematics was observed. Neither knee- nor hip-joint kinematics was affected by pedaling cadence or workload effects.

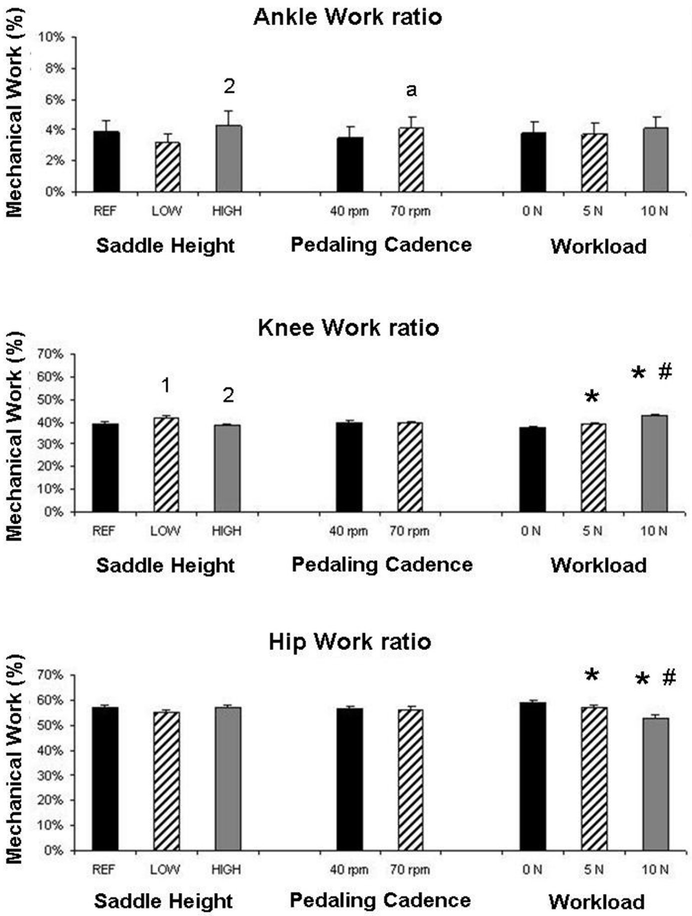

Figure 5 — Mean (± SE) results of the ratio of ankle, knee, and hip joints to the total mechanical work in the 3 saddle heights (reference [REF], high, and low), 2 pedaling cadences (40 and 70 rpm), and 3 workloads (0, 5, and 10 N). [1]Significant difference related to REF ($P < .05$). [2]Significant difference related to LOW ($P < .05$). [a]Significant difference related to 40 rpm ($P < .05$). *Significant difference related to 0 N ($P < .05$). #Significant difference related to 5 N ($P < .05$).

Discussion

The lack of evidence regarding the control of joint mechanical work and kinematics while changing saddle height, pedaling cadence, or workload has impaired a better understanding of the coordinative pattern of noncyclists during rehabilitation cycling. The aim of the current study was to compare the effects of different saddle heights, workloads, and pedaling cadences on the 3 lower limb joints' mechanical work and kinematics.

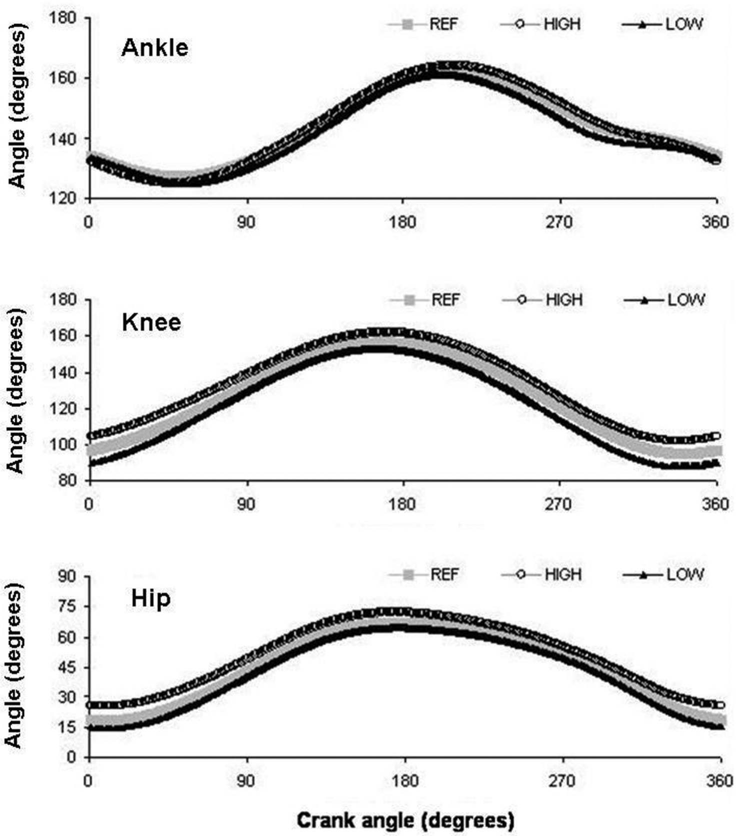

Figure 6 — Representative data for the joint angle from 1 subject performing at the reference [REF], high, and low saddle heights at 70 rpm and 10 N of workload.

Saddle Height's Effects

Controversial results have been obtained for saddle height's effects on joint mechanics and kinematics. Gonzalez and Hull[17] observed saddle height's effects on hip- and knee-joint moments, and Rugg and Gregor[18] and Sanderson and Amoroso[19] described its effects on joint kinematics. However, gaps are observed regarding mechanical work of lower limb joints when saddle height is changed. Our results indicate that knee-joint contribution to TMW was inversely related to saddle height. Nevertheless, knee work contribution was only different when saddle height was changed from high to low, with no differences from reference saddle height, which is in agreement with previous studies.[13] Changes in saddle height were related to knee loads, as reported by Ericson and Nisell,[23] who observed increased patellofemoral-joint compressive force as saddle height was reduced. The increased mechanical work at the knee joint can be related to higher quadriceps force,[9] which results in overload on soft tissues (ie, patellofemoral cartilage).[23] In the current study,

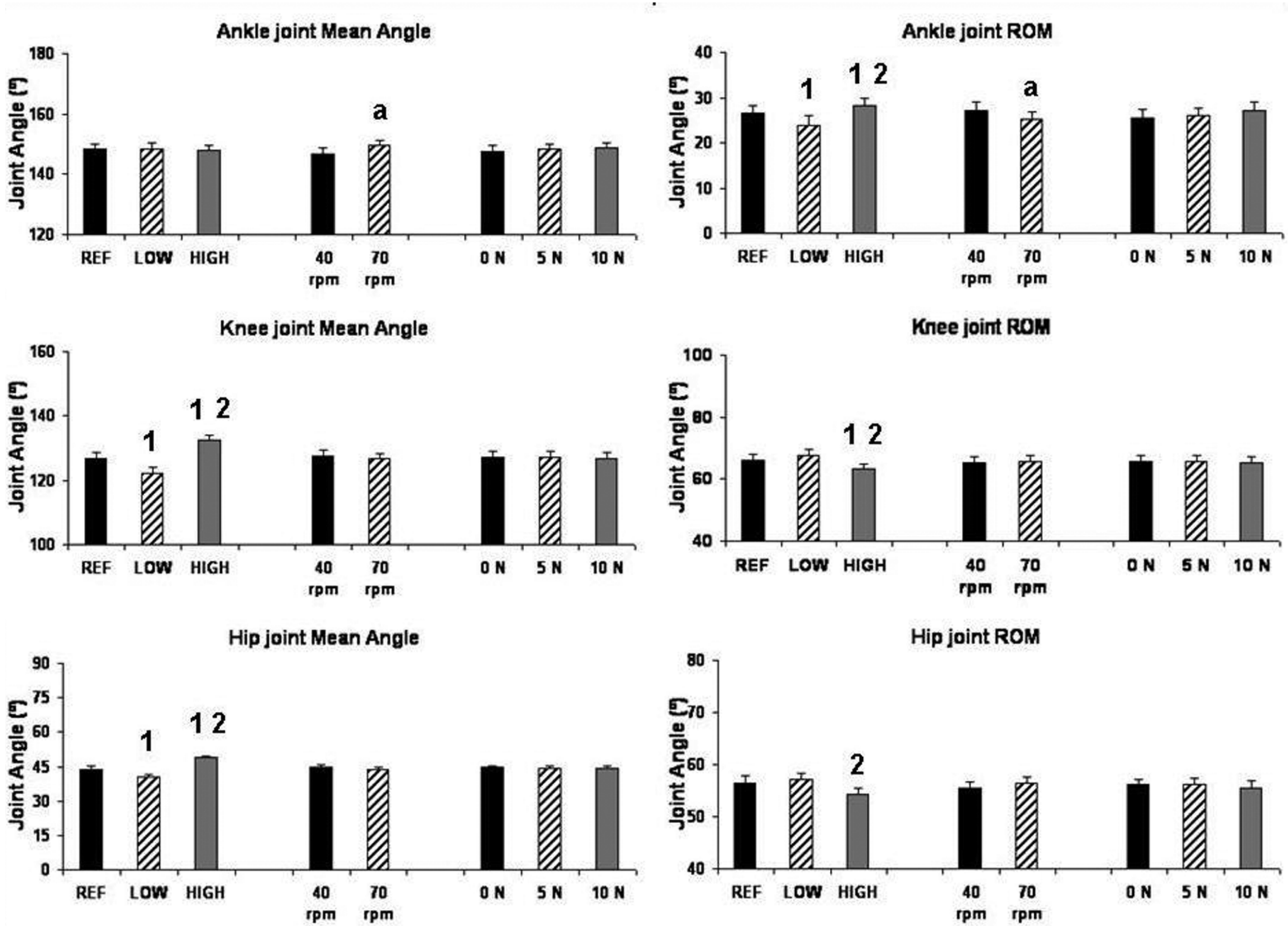

Figure 7 — Mean (± SE) results of mean angle and range of motion (ROM) of ankle, knee, and hip joints at the 3 saddle heights (reference [REF], high, and low), 2 pedaling cadences (40 and 70 rpm), and 3 workloads (0, 5, and 10 N). [1]Significant difference related to REF ($P < .05$). [2]Significant difference related to LOW ($P < .05$). [a]Significant difference related to 40 rpm ($P < .05$). No significant differences regarding workload effects.

there was an increased contribution of the knee joint to TMW when the saddle height was lowered 3 cm. These results indicate that when using a stationary cycle ergometer for subjects with knee injury or anterior pain, saddle height should not be set lower than 3 cm below the trochanteric height to prevent the occurrence of chondromalacia or patellofemoral syndrome.[24] The inverse relationship observed between knee-joint angle and anterior cruciate ligament strain[8] also indicates that the low saddle height should be avoided.

Higher saddle height resulted in an increased contribution of the ankle joint to TMW compared with low saddle position. Some of the observed changes in mechanical work contribution of the ankle and knee joints were based on kinematics changes that were partially observed by Diefenthaeler et al[14] and Nordeen-Snyder.[16] Both studies reported changes in ankle-joint kinematics, suggesting that this joint would perform a role in controlling force application on the pedal. Ankle-joint muscles' coactivation (ie, tibialis anterior and soleus) and joint kinematics have been suggested to affect the effectiveness of force transfer from the limbs to the crank.[6,25] Therefore, the reduced contribution of the knee joint to TMW at the high saddle position was balanced by an increase in the ankle joint's contribution. This strategy has not been reported in the literature, mainly because the ankle joint has been suggested to work primarily as a force transferrer from the limbs to the crank.[6,25–28] Nevertheless, most of ankle joint's role has been suggested to concern high-skill cycling movement, which is only observed in trained cyclists.[29] An increased contribution of ankle joint with increased saddle height would have occurred because of the less skilled movement by the evaluated subjects. Chapman et al[29] indicated that training level and experience affect muscle-activation pattern, which might change the contribution of each joint to TMW. However, only pedaling cadences were compared in that study,[29] with no reports on saddle height or workload effects.

Ankle-, knee-, and hip-joint kinematics have been affected by saddle height changes, as previously described.[16] Rugg and Gregor[18] measured lower limb joint ROM with 15% of change in the saddle height, finding that the knee joint was the most affected. On the contrary, Diefenthaeler et al[14] reported that only ankle-joint kinematics were affected by saddle height, but they evaluated only 3 subjects, which prevents any definitive conclusion regarding the effects of saddle position on knee-joint loads and kinematics. With changing saddle height, the control of joint mechanical work could depend on changes in kinematics. This hypothesis is based on the inverse relationship between hip- and knee-joint ROM and saddle height's and joint angular velocity's effects on joint mechanical work. Sanderson et al[12] reported that increased ROM of the ankle joint is related to changes in muscle-shortening velocity, which might affect ankle- muscle force production. We can infer that the central nervous system controls muscles' range of lengthening and shortening velocity to maximize muscle power production.[12]

Pedaling Cadence's Effects

Divergence among studies has been observed regarding the contribution of each joint to TMW or the total lower limb joint moments.[11,26] The current study indicated that hip- and knee-joint contribution to TMW did not change with increased pedaling cadence, as reported by Ericson.[9] However, ankle-joint contribution increased when pedaling cadence was increased from 40 to 70 rpm. As observed with saddle height, pedaling cadence affected ankle work contribution, which has not been found in previous studies.[9,11,26] The lower skill of pedaling movement of the noncyclists evaluated in the current study seems to be the main reason for the increased contribution of the ankle joint to TMW when pedaling cadence was increased. Ankle-joint contribution could also be explained by the changes in ankle-joint kinematics, which have been previously described to be related to a shift in muscle-lengthening and -shortening velocity.[12]

Workload's Effects

Ericson and Nisell[23] reported evidence of the effects of workload on patellofemoral-joint force, but they did not evaluate the effects of small changes in workload on joint mechanical work. In the current study, we measured lower limb joint mechanical work for a workload that had 11 ± 0.9 W as the lower bound (for 0 N and 40 rpm) and 59 ± 2.7 W as the upper bound (for 10 N and 70 rpm). Neither studies on cycling performance nor those on the use of stationary cycle ergometry for rehabilitation have measured such a low workload. Ericson and Nisell[9,23] compared the increase of workload from 0 W to 120 W, and Fleming et al[4] evaluated subjects cycling at 75 W and 60 rpm. Those studies indicated that stationary cycling is a valuable exercise for knee-injured subjects, mainly because of the possibility to improve joint mobility when the workload is set at a minimum or no load. The current study suggests that a small increase in workload can increase joint mechanical work, which may be useful in rehabilitation procedures.

Unlike previous studies,[30] lower limb kinematics were not significant affected by workload, which reinforces the small effects of workload variation used in the current study. The effects of workload on joint kinematics have been previously described,[30] but they were evaluated at a higher workload than that of the current study.

Our study was designed to complement the results of Ericson's series of studies,[3,15,23] mainly the analysis of each joint's contribution to TMW at low workload. Our understanding of the coordinative pattern has been clarified through the increase of ankle-joint contribution at a high saddle position, which seemed to be a compensatory strategy for the lower knee-joint contribution. The kinematics of the ankle, knee, and hip joints also changed with saddle height in an attempt to maintain muscle power production. The increase of ankle work contribution and kinematics with the change of pedaling cadence has been suggested to indicate poor pedaling-movement skill, because the ankle joint is expected to work mainly as a force transferrer from the limbs to the crank.[6,26–28] Future studies should be conducted with a focus on computing joint load with muscle-force simulation through a forward dynamics model while changing saddle height, pedaling cadence, and low workload.

Conclusion

The manipulation of saddle height, pedaling cadence, and workload affected the coordinative pattern of noncyclists pedaling on a stationary cycle ergometer at workloads similar to those used during rehabilitation. An increased contribution of the ankle joint to TMW with increased saddle height and pedaling cadence indicated ankle-joint muscles tuning to control pedal force application. At the high saddle position it could also be inferred that the ankle joint compensated for the reduced knee-joint work contribution, which was probably effective for minimizing soft-tissue damage to the knee joint (ie, anterior cruciate ligament and patellofemoral cartilage).

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