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The effect of combined isometric and plyometric training on musculotendinous ankle stiffness and its subsequent effect on performance in international age-group track sprint cycling

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ABSTRACT

Within sprint cycling, the ankle's primary role is transferring power generated at the hip and knee. However, a stiffer musculotendinous unit around the ankle may directly contribute to increased performance. The aim of this study was to measure the influence of isometric and plyometric training on ankle stiffness and sprint cycling performance. Fifteen international age-group sprint track cyclists completed a 10-week intervention. An experimental group ($n = 8$) performed high-volume plyometrics and isometric calf raises in addition to their normal training, whilst a control group ($n = 7$) continued with no intervention. Kinetic measures were recorded on a force plate and in sprints on an isokinetic ergometer at 60 and 135 rev/min. Kinematic measures were recorded using high-speed cameras and reflective markers. Isometric peak force during plantar flexion and vertical ankle stiffness when hopping were both increased in the intervention group ($p \leq 0.05$). Bicycle sprints showed group differences in ankle stiffness ($p = 0.01$) at 135 rev/min and average ankle angle ($p = 0.04$) at 60 rev/min. Therefore, combined plyometrics and isometrics were an effective method for increasing ankle stiffness. This combination of stimuli also effected the utilisation of the ankle in sprint cycling.

1. Introduction

Track sprint cycling performance is determined by the relationship between propulsive power and resistance to forward motion (Martin et al., 2007). The latter is influenced by aerodynamics, mass, and rolling resistance or friction (Martin et al., 2007). Propulsive power depends on the linear relationship between pedalling rate (cadence) and torque at the pedal. Therefore, when all else remains equal, an increase in either peak pedalling rate or peak torque will elicit improvements in peak propulsive power. Whilst pedalling rate is reflective of coordinative and technical abilities, the ability to apply torque is largely determined by maximal neuromuscular force (Martin et al., 2007). This notion is supported by a body of evidence suggesting that maximal force production contributes to track sprint cycling performance (Barratt, 2014; Stone et al., 2004). As the largest instances of torque occur at low pedalling rates, start performance sees the highest contribution of maximal force production. As pedalling rate increases, the time available to apply force is reduced (downstroke <250 ms at 120 rev/min); consequently, the rapid production of force also becomes imperative to performance (Martin et al., 2007), particularly during flying sprint efforts.

The ankle's primary function during sprint cycling is to transfer power, produced at the knee and the hip, to the pedal (Kautz & Neptune, 2002; Kordi et al., 2017; Martin & Nichols, 2018; McDaniel et al., 2014). This notable action is demonstrated by the greater specific strength at the ankle displayed by elite track sprint cyclists when compared to sub-elite athletes (Barratt, 2014). Theoretically, improving the stiffness of the ankle joint should increase the capabilities of the ankle to transfer energy, created by the hip and knee, to the pedal. Previous research has shown stiffness to be related to increased performance in various sports, especially those associated with high levels of strength and power (Arampatzis et al., 1999; Belli & Bosco, 1992; Butler et al., 2003).

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In physics, stiffness is described by Hooke's law (F = kx) where F is the force required to deform an object, k is the proportionality constant and x is the distance the object is deformed. In physiological terms, stiffness is the ability of a joint or multi-joint system to resist deformation against an external force (Latash & Zatsiorsky, 1993). Therefore, increased stiffness could be achieved through an increase in either force production or a reduction in displacement at a joint or a combination of both. In cycling, an increase in stiffness will be seen through either a reduction in displacement or an increase in torque production.

Previously, increases in dynamic joint stiffness have been facilitated through either isometric or plyometric training interventions (Kubo et al., 2001, 2007, 2017) and to the best of our knowledge no study has utilised both training paradigms. A combination may increase the probability of adaptation, with research on the mechanism of musculotendinous changes still inconclusive (Burgess et al., 2007; Kubo et al., 2007, 2017). Therefore, the primary aim of this study was to assess the effect of both isometric and plyometric training on ankle stiffness, torque, and power, during sprints on a bicycle ergometer at low pedalling rates (60 rev/min) to indicate the effect on sprint cycling start performance. A secondary aim was to assess the effects of the intervention on performance during sprints on a bicycle ergometer at high pedalling rates (135 rev/min) to infer the effects on other aspects of sprint cycling.

2. Methods

2.1. Participants

International age-group sprint track cyclists (10.0-11.8 s flying 200 m time) participated in the study, consisting of an experimental group (EXP, 5 female and 3 male, 18 ± 1 years, 70.1 ± 12.3 kg, 1.71 ± 0.1m) and a control group (CON, 2 female and 5 male, 16 ± 1 years, 71.4 ± 7.5 kg, 1.72 ± 0.1m). Participants were allocated to groups by national governing body squad status, coaching group and location in the country. This meant that all those in the control group were younger, and that those in the experimental group were more highly trained. All participants were international age-group track sprint cyclists' and had 1-3 years resistance training experience. Participants were free from musculoskeletal injury for at least 12 months before the study started. Project approval was gained through the local university ethics committee, in line with the declaration of Helsinki. Parental or guardian assent was obtained for participants under the age of 18 years.

2.2. Procedures

This study used a non-randomised control trial design, which incorporated a 10-week intervention of high-volume plyometrics' and maximal isometric calf raises. Pre- and post-intervention measures of stiffness were recorded during sprints on an isokinetic cycle ergometer and during unilateral hopping on a force plate. Sprint cycling performance was also established pre- and post-intervention, using an isokinetic cycle ergometer at both low (60 rev/min) and high (135 rev/min) pedalling rates. Further measures of musculotendinous performance at the ankle were taken pre- and post-intervention to measure if changes in ankle strength that could influence cycling performance.

2.3. Ankle Stiffness

The methods and equipment used in this study to calculate ankle stiffness and other on-bike measures were based on previous research (Burnie et al., 2020). An isokinetic ergometer (SRM Ergometer, Julich, Germany) was set up to replicate each participant's track bicycle position, with a crank length of 165 mm. The modified ergometer flywheel was driven by a 2.2-kW AC induction motor (ABB Ltd, Warrington, UK). The motor was controlled by a frequency inverter equipped with a braking resistor (Model: Altivar ATV312 HU22, Schneider Electric Ltd, London, UK). This set-up allowed participants to start their sprints at the desired pedalling rate, rather than expending energy in accelerating the flywheel. The ergometer was fitted with Sensix force pedals (Model ICS4, Sensix, Poitiers, France) and a crank encoder (Model LM13, RLS, Komenda, Slovenia), sampling data at 200 Hz. Normal and tangential pedal forces were resolved using the crank and pedal angles into the effective (propulsive) and ineffective (applied along the crank) crank forces.

Riders undertook their standard warm-up on the ergometer at a self-selected pedalling rate and resistance for at least 10 min, followed by a warm-up sprint at 135 rev/min. Then riders performed two x 4 s seated sprints at a pedalling rate of 135 rev/min on the isokinetic ergometer with 4 min recovery between efforts. This process was repeated at 60 rev/min for each participant. 60 rev/min was the chosen pedalling rate as it is a rate required during standing start initial acceleration phase (Gardner et al., 2007), it has been used as a measure of cycling specific strength (Barratt, 2014).

Two-dimensional kinematic data of the participants' left side were recorded at 100 Hz using one high speed camera with infra-red ring lights (Model: UI-522xRE-M, IDS, Obersulm, Germany). The camera was perpendicular to the participant, centred on the ergometer and set 3 m away. For all sessions, the same researcher attached reflective markers on the pedal spindle, lateral malleolus, lateral femoral condyle, greater trochanter and iliac crest. Kinematics and kinetics on the ergometer were recorded by CrankCam software (Centre for Sports Engineering Research, SHU, Sheffield, UK), which synchronised the camera and pedal force data (down sampled to 100 Hz to match the camera data) and was used for data processing, including auto-tracking of the marker positions.

All kinetic and kinematic data were filtered using a Butterworth fourth order (zero lag) low pass filter, using a cut-off frequency of 8 Hz (Morrissey et al., 1995). Instantaneous left crank power was calculated from the product of the left crank torque and the crank angular velocity. Ankle angle was defined as the internal angle between the shank and foot segments. Ankle joint moments were calculated via inverse dynamics, using pedal forces, limb kinematics, and body segment parameters (de Leva, 1996). Ankle joint powers were determined by taking the product of the net ankle joint moment and ankle joint angular velocity. Data were analysed using a custom Matlab script (R2017a, MathWorks, Cambridge, UK). Each sprint lasted for 4 s, thus providing four and six complete crank revolutions at 60 rev/min and 135 rev/min, respectively. Crank forces and powers, ankle joint angles, moments and powers were resampled to 100 data points around the crank cycle and then mean value at each time point was calculated to obtain a single ensemble-averaged time series for each trial. Peak instantaneous crank power (PPO), peak effective crank force (FPE), peak ankle power (PANKLE), peak ankle extension moment (MANKLE) and average ankle angle over a complete crank revolution (AANKLE) were also calculated for each trial and averaged over the two trials in each session to obtain pre- and post-intervention. The ratio of change in joint moment to change in joint angle during dorsiflexion of the ankle in the downstroke of the crank cycle was calculated and used as the measure of on-bike ankle stiffness (KANKLE).

Off-bike vertical stiffness (KVERT) was established using an adaptation of previous protocols (McLachlan et al., 2006; Pena-González et al., 2019). The relationship between peak ground reaction force and the maximum displacement of centre of mass (taken from a marker on the anterior superior iliac spine) during the foot contact of a single hop was calculated to provide the metric. Participants were instructed to hop as high as they could with hands on hips, at a frequency greater than 2.2 Hz to ensure that the ankle joint was the primary regulator of stiffness (Farley & Morgenroth, 1999; Hobara et al., 2010, 2013). Data were collected once steady state hopping was achieved. Hopping trials were filmed on the sagittal plane from the left-hand side with a high-speed video camera, recording at 240 Hz (iPhone model 6s, Apple Inc. Cupertino, California, USA) and centre of mass displacement was calculated using Quintic video analysis software (Version 31, Quintic Consultancy Ltd. Birmingham, UK). Only one aspect of the body was filmed as no significant bilateral difference has been observed for unilateral hopping at this frequency (2.2 Hz) (Brauner et al., 2014; Hobara et al., 2013). This was consistent with the bicycle ergometer trials, where only the left side was filmed. The force data were collected on a force plate recording at 1000 Hz (NMP Technologies Ltd., London, UK).

2.4. Maximal Isometric Force

Peak Isometric force (FISO) was measured using a single-leg isometric standing calf raise performed on an adjustable rack. The rack was bolted to the floor and placed around the top of a Force Decks force platform unit (NMP Technologies Ltd., London, UK) measuring at 1000 Hz. Athletes were instructed to maintain neutral hip alignment and full extension of the knee and hip throughout the trial, with the bar resting on their shoulders. Coronal foot position and level of plantar flexion was self-selected to provide self-optimisation. The height of the bar was recorded for consistency across trials for each participant. The maximal isometric force was calculated from the mean of 3 x 5 s maximal contractions, interspersed by 30 s rest.

2.5. Concentric Mean Force

The average of two maximal straight legged concentric plantar flexion ‘jumps’ were also performed on the same force plate to provide a measure of concentric neuromuscular force (FCON). Participants were instructed to place hands on hips and jump with no countermovement, using aggressive plantar flexion. Full extension of the knee and hip were used throughout to ensure isolation of the plantar flexors. Concentric mean force was measured to align the protocol with studies of ankle strength and stiffness (Burgess et al., 2007). The participants performed three familiarisation sessions in the week prior to testing.

2.6. Intervention

The 10-week training intervention utilised both isometric and plyometric training. Isometric resistance training increases the stiffness of the tendon and muscles in the ankle; Gastrocnemius (GAS), Soleus (SOL), and Tibialis Anterior (TA). Improved muscle stiffness allows more lengthening of the tendon (Massey et al., 2018; McMahon et al., 2012), which will increase the storage of elastic energy. The training intervention consisted of two main exercises: maximal isometric calf raises and high-volume low-intensity plyometric contacts in the form of intensive pogo jumps that were progressed over 10 weeks (Table 1; Fouré et al., 2010; Jeffreys et al., 2019). EXP completed both protocols in conjunction with their regular programme, whilst CON continued their normal training.

Table 1: Protocol and progression used for isometric and plyometric interventions used by EXP.

Plyometric Protocol										
Week	1	2	3	4	5	6	7	8	9	10
Contacts per session	100	100	100	200	200	200	300	300	300	300
Total weekly contacts	300	300	300	600	600	600	900	900	900	900
Isometric Protocol										
Week	1	2	3	4	5	6	7	8	9	10
Volume per session	3 x 5 s	3 x 5 s	3 x 5 s	3 x 8 s	3 x 8 s	3 x 8 s	3 x 10 s	3 x 10 s	3 x 10 s	3 x 10 s
Total weekly volume	45 s	45 s	45 s	72 s	72 s	72 s	90 s	90 s	90 s	90 s

The overall content of the training programmes was prescribed collaboratively by the authors' and the participants cycling coaches. Cycling content included at least two track cycling sessions consisting of low-cadence technical standing starts and high-cadence, flying sprint efforts. One low-intensity road ride of about 45 to 60 minutes in length was also completed each week. Gym-based strength training sessions included traditional resistance training exercises: squats, leg press and deadlift. The weight lifted, number of repetitions, number of sets, and all supplementary exercises were prescribed by the authors.

2.7. Statistical Approach

Statistical analyses were performed using SPSS Statistics (Version 24, IBM, Chicago, Illinois, USA). A one-way ANCOVA with baseline as a covariate was used to assess the differences between groups for on-bike (KANKLE, PPO, FPE, PANKLE, MANKLE, AANKLE) and off-bike measures (KVERT, FCON, FISO). Where main effects of groups were found, a pairwise comparison was performed for the control and intervention group. Additionally, 95% confidence intervals (CI) and Cohen's effect sizes (d) were calculated to assess the magnitude of change from pre- to post-intervention. Effect sizes were interpreted using Cohen's classification system: effect sizes between 0.2 and 0.5 were considered small, between 0.5 and 0.8 were considered moderate, and greater than 0.8 were considered large (Cohen, 1969). The level of statistical significance was set to; $p \leq 0.05$ and all data is presented as group mean difference ± standard error (SE).

3. Results

3.1. Off-bike Measures

A group effect for was found for KVERT ($F(1,12) = 8.1$, $p = 0.02$), with greater KVERT post-intervention shown in the EXP (62.6 ± 22 N.cm-1, 95% CI [14.7, 110.5]) (Figure 1). The pre-to-post increase in KVERT was large in EXP (d = 1.20), whilst it was small in the control group (CON (d = 0.41). In FISO, a group effect was apparent ($F(1,12) = 4.9$, $p = 0.04$), with greater force shown post intervention in EXP compared to CON (173.6 ± 78.8 N; 95% CI [2, 345]) (Figure 1). Increases in EXP showed a moderate increase (d = 0.79) with only a trivial change in CON (d = 0.08). There was no group effect observed for FCON (Figure 1).

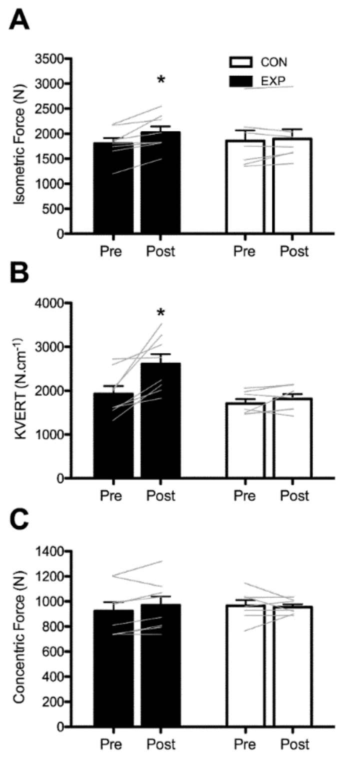

Figure 1: Individual responses and group mean changes from pre- to post-intervention. (A) Mean changes in FISO. (B) Mean changes in KVERT. (C) Mean changes in FCON. * denotes a significant difference between pre- and post-intervention measures ($p < 0.05$).

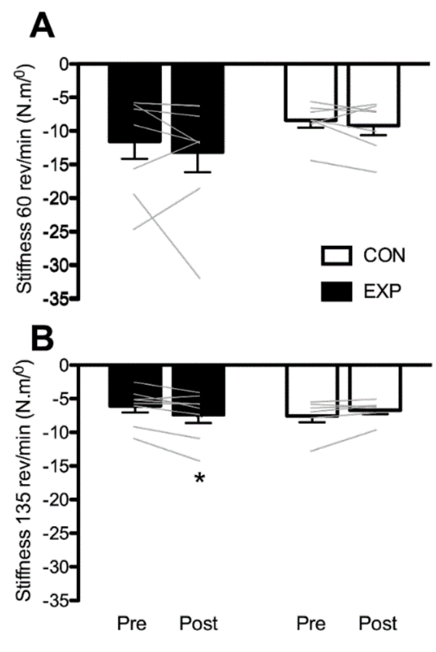

Figure 2: Individual and group mean traces for changes in ankle stiffness (KVERT) from pre- to post-intervention. (A) Mean and individual changes 60 rev/min (B) Mean and individual changes 135 rev/min * denotes a significant difference between pre- and post-intervention measures ($p < 0.05$).

3.2. Bicycle Isokinetic Ergometer Measures

In the 135 rev/min trials on the isokinetic ergometer, the one-way ANCOVA showed a group effect in KANKLE ($F(1,12) = 9.6$, $p = 0.01$), with pairwise comparisons showing EXP to be stiffer when compared to CON (2.1 ± 0.7 N.m/°, 95% CI [0.6, 3.5] (Figure 2). An increase was shown in the EXP (d = 0.45) compared to a decrease in the CON (d = -0.45). AANGLE, PPO, FPE, PANKLE, and MANKLE all showed no group effects in the 135 rev/min trials (Table 1). At 60 rev/min there was a group effect in AANGLE ($F(1,12) = 5.2$, $p = 0.041$) with the EXP showing a greater ankle angle through a crank cycle (2.9 ± 1.3°, 95% CI [0.1, 5.7]; Figure 3). EXP showed a moderate increase (d = 0.45) pre to post-intervention compared to a trivial change in CON (d = 0.01) group. There was no significant change in PPO at 60 rev/min ($F(1,12) = 4.45$, $p = 0.06$), with a small effect (d = 0.21) for CON, compared with a trivial change (d = 0.03) for EXP group. All other trials at 60 rev/min showed non-significant results (KANKLE, PPO, FPE, PANKLE, and MANKLE; Table 2).

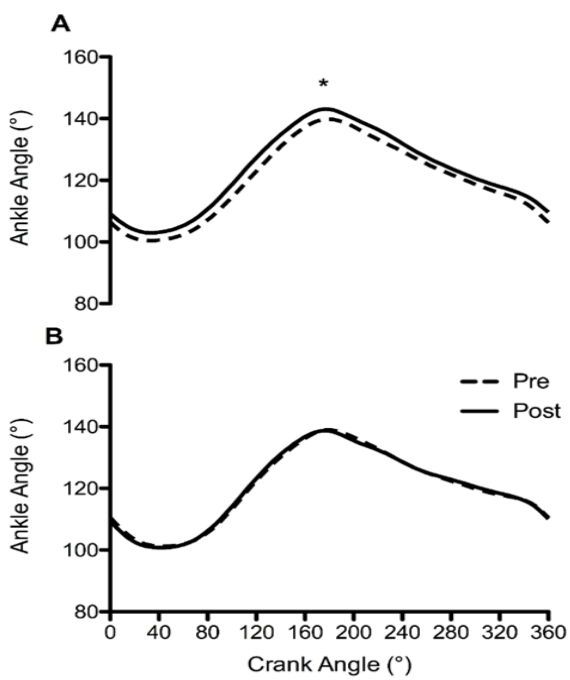

Figure 3. Group mean ankle angle throughout the crank cycle at 60 rev/min. (A) EXP (B) CON. * denotes a significant difference between pre- and post-intervention measures. compared the average ankle angle during a complete crank revolution (AANGLE) ($p < 0.05$)

4. Discussion

The main findings from this study were that combining plyometrics and isometric training increased vertical stiffness when hopping, and isometric force production at the ankle in a group of international age-group track sprint cyclists. During maximal cycling efforts, an increase in performance was not observed but ankle stiffness was increased at high cadence. The average ankle angle during a pedal cycle was also increased at the lower cadences that are representative of track sprint cycling starts.

4.1. Vertical Stiffness, Isometric Peak Force and Concentric Mean Force

Following the training intervention, there was a large increase in vertical stiffness of the ankle joint in the experimental group demonstrating that the training intervention was successful. Large increases in dynamic stiffness at a joint is in conjunction with previous research that facilitated either isometric or plyometric training interventions separately (Kubo et al., 2001, 2007, 2017). As research into the mechanism of musculotendinous changes is still inconclusive (Burgess et al., 2007; Kubo et al., 2007, 2017), a combination was used to increase the likelihood of adaptation. To the best of our knowledge this is the first study that has utilised both training paradigms.

Research has shown isometric exercise to cause optimal adaptations to elastic components of the musculotendinous unit (Kubo et al., 2001, 2007). Kubo et al. (2017) demonstrated that a plyometric intervention, similar to those used in this study, caused an adaptation to muscle fibre stiffness, whilst isometric interventions caused an increase in tendon stiffness. Conversely, (Burgess et al., 2007) compared the effect of a similar intervention on tendon stiffness and showed negligible differences in outcomes. Both protocols used in the current study have been shown to improve tendon stiffness, but there is mixed evidence regarding changes in musculature. Increases in the isometric measure would therefore infer adaptations to the tendinous component in the ankle. Consequently, any increases in concentric measures may indicate changes to musculature as the mechanism, due to the concentric only action negating any influence from the tendon (Kubo et al., 2001, 2007, 2017). The absence of any increase in concentric mean force from this study, indicates that the tendon rather than the musculature has been most influenced by the intervention. However, conclusions involving the mechanism of adaptation must be made with caution as the musculature and tendinous tissue in the musculotendinous unit is linked in a somewhat inextricable manner (Burgess et al., 2007; Oranchuk et al., 2019). Furthermore, the protocols used in the training intervention, consisting of bilateral hopping and maximal isometric calf raises, were similar kinematically to tests in which increases were seen.

4.2. Cycling Performance

Increases in ankle stiffness were seen at the pedalling rate of 135 rev/min. The comparable contact times in the pogo jumps and time available to apply force at 135 rev/min (both <250 ms) might have been a contributing factor. This connection provides further indication of a tendinous response to the intervention. Increases in cycling specific performance (peak crank power and peak effective force) were not seen at 135 rev/min but the evidence presented below suggest that the changes caused may enhance the

Table 2: Group mean and standard error for all non-significant variables from bicycle ergometer.

60 rev/min

	K_{ANKLE} (N.m/°)		F_{PE} (N)		PPO (W)		M_{ANKLE} (N.m)		P_{ANKLE} (W)	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
EXP	-11.6 ± 2.6	-13.2 ± 3.0	919.8 ± 60.3	966.6 ± 52.2	921.1 ± 55.7	926.0 ± 42.9	121.1 ± 9.9	127.6 ± 8.4	315.7 ± 16.4	328.3 ± 21.9
CON	-8.5 ± 1.1	-9.2 ± 1.4	974.0 ± 78.3	1044.6 ± 64.3	1037.5 ± 104.9	1084.9 ± 68.0	138.4 ± 8.0	137.4 ± 12.7	404.6 ± 34.5	371.1 ± 26.8

135 rev/min

	A_{ANGLE} (°)		F_{PE} (N)		PPO (W)		M_{ANKLE} (N.m)		P_{ANKLE} (W)	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
EXP	122.3 ± 2.1	123.8 ± 2.0	641.0 ± 42.8	648.8 ± 39.2	1447.5 ± 121.4	1538.9 ± 72.3	83.3 ± 8.5	86.1 ± 7.6	362.2 ± 42.6	362.6 ± 39.7
CON	132.0 ± 1.4	122.1 ± 1.6	688.5 ± 55.1	717.1 ± 52.6	1441.3 ± 138.2	1595.7 ± 140.1	95.5 ± 7.4	97.2 ± 8.5	384.4 ± 45.0	419.8 ± 48.2

Note. K_{ANKLE}, Ankle stiffness (60 rev/min only); A_{ANGLE}, Ankle angle (135 rev/min only); F_{PE}, Peak effective force; PPO, Peak power; M_{ANKLE}, Ankle moment; P_{ANKLE}, Ankle power.

efficiency of power production at the ankle with a period of cycling specific training. Increased stiffness has consistently been shown to have a positive impact on performance in other explosive strength and power sports (Arampatzis et al., 1999; Belli & Bosco, 1992; Bret et al., 2002). McDaniel et al. (2014) demonstrated that as pedalling rate increases the contribution of the ankle to crank power reduces, which may be a partial explanation for the absence of increase in peak crank power and peak effective force at 135 rev/min. An increase in ankle stiffness with no significant increase in ankle moment suggests that less displacement has occurred at the joint. Reducing the displacement of the ankle joint during cycling has been shown to occur with practice, and to coincide with an improvement in the efficiency of pedalling (Hasson et al., 2008). If the physiological capability of the lower limbs is increased further, then a performance increase may occur. In well-trained athletes, the magnitude and time course of adaptations is smaller and slower than the non-trained population (Till et al., 2017), indicating that these effects could be optimised further by a longer or more intense training period.

An increase in average ankle angle, but not ankle stiffness, occurred at lower pedalling rate. At 60 rev/min a more plantar flexed position was utilised by the cyclists following the intervention, but changes in displacement and ankle moments were not found. These findings are comparable to those found after the implementation of single-leg cycling drills (Hasson et al., 2008) and suggests that the intervention may have facilitated an enhancement in pedalling, but through improvements in musculotendinous qualities rather than coordination. The absence of any increase in ankle stiffness at 60 rev/min may be due to reduced transfer of physiological qualities to the lower pedalling rate trials. During a sprint cycling start, where lower pedalling rates are experienced, the cyclist will be in a standing position and would not become seated until a higher pedalling rate was reached.

Unfortunately, this position cannot be replicated reliably on a bicycle ergometer and, consequently, all efforts are performed seated (Wilkinson et al., 2020). Biomechanical specificity has been consistently shown to be an important aspect of transfer of training in elite athletes. Factors that contribute to transference include; contraction type, joint angle, posture and limb position, and velocity of contraction (Morrissey et al., 1995; Stone et al., 2004; Wilson et al., 1996). During the 60 rev/min trials, participants were performing a skill with familiar contraction types and velocities but unfamiliar joint angles, limb angles, and posture. This may provide an explanation for the adaptation in vertical stiffness not having transferred as effectively to lower pedalling rates when compared to higher pedalling rates that were completed in a seated bicycle position.

At 60 rev/min, increases in PPO by CON approached significance, and the effect size was large. This might have been caused by the younger training and chronological age of the athletes in this group, rather than any effect of the intervention. Larger adaptations are consistently shown by less mature athletes or athletes of younger training age for strength and power training (Pena-González et al., 2019; Till et al., 2017). However, this makes adaptations in the other variables measured, by the older, more highly trained group following the intervention more noteworthy. Lower-body maximal force production is correlated to peak power output and performance in sprint cycling (Stone et al., 2004). Like in any other sport, there is a coordinative aspect, and stronger athletes must be able to apply force in a specific modality. To improve ankle performance on a bike, it has been suggested that specific learning in a cycling modality is needed (Hasson et al., 2008; Kordi et al., 2017; McDaniel et al., 2014). This research suggests changes can occur through more general training. These structural qualities may provide the foundation for later coordinative properties to be built upon in a more specific modality (Flanagan & Comyns, 2008). Increases in average ankle angle seen at 60 rev/min could also provide a future benefit to performance through efficiency. Anderson et al. (2007) showed through mathematical modelling that larger voluntary torques are created at larger ankle angles. Increases in ankle angle will allow athletes to increase forces expressed by the ankle. Assuming change in angle does not affect the contribution from limbs further up the chain, force applied to the pedal will increase and ultimately improve sprint cycling performance. Therefore, a performance increase may occur with further specific sprint cycling practice or with a longer intervention to allow for maximal transfer of training (Till et al., 2017; Young, 2006).

Combined high volume plyometric hopping and isometric strength training is an effective method for increasing stiffness and force production at the ankle in international age-group sprint track cyclists. Similar interventions are recommended for those seeking to enhance performance in sprint track cycling and may offer benefits to other sports requiring high levels of ankle stiffness. Coaches working with sprint track cyclists should consider the use of a plyometric and isometric calf raises in additional to the athletes' traditional track cycling and strength training programmes.

Conflict of Interest

The authors declare no conflict of interests.

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