The Effect of Flywheel Complex Training with Eccentric-Overload on Muscular Adaptation in Elite Female Volleyball Players

Jiaoqin Wang[1,2], Qiang Zhang[2†], Wenhui Chen[3], Fuhong Hao[4], Ming Zhang[1*], Yongzhao Fan[2*]

Abstract

This study aimed to compare the effects of 8 weeks (24 sessions) between flywheel complex training with eccentric overload and traditional complex training of well-trained volleyball players on muscle adaptation, including hypertrophy, strength, and power variables. Fourteen athletes were recruited and randomly divided into the flywheel complex training with an eccentric-overload group (FCTEO, n = 7) and the control group (the traditional complex training group,   TCT, n = 7). Participants performed semi-squats using a flywheel device or Smith machine and drop jumps, with three sets of 8 repetitions and three sets of 12 repetitions, respectively. The results which were measured included the muscle thickness at the proximal, mid, and distal sections of the quadriceps femoris, maximal semi-squat strength (1RM-SS), squat jump (SJ), countermovement jump (CMJ), and three-step approach jump (AJ). In addition, a two-way repeated ANOVA analysis was used to find differences between the two groups and between the two testing times (pre-test vs. post-test). The results of the FCTEO group showed a significantly better improvement ($p < .05$) in CMJ (height: ES= .648, peak power: ES= .750), AJ (height: ES= .538, peak power: ES =.478), 1RM-SS (ES= .671), and the muscle thickness at the mid of the quadriceps femoris (ES= .504) compared to the TCT group. Since volleyball requires lower limb strength and explosive effort during repeated jumps and spiking, these results suggest that FCTEO affects muscular adaptation in a way that improves performance in well-trained female volleyball players.

Keywords： female volleyball players, hypertrophy, strength, power, flywheel complex training

Introduction

In competitive team sports such as basketball, volleyball, and American football, muscle strength and power are essential because they form the basis for performance-determining activities such as jumping, running, and hitting. Sheppard et al. stated that the ability to jump is critical to success in volleyball because it allows for a competitive advantage on offense (greater height to hit over the block/greater angle of attack) and also on defense (achieving a higher block position) (Sheppard et al., 2007; Sheppard et al., 2008a; Sheppard et al., 2008b). The strength and power of an athlete's lower limbs account for the majority of their jumping capacity. (Young et al., 1999).

Power equals strength multiplied by velocity(Cardinale et al., 2011). This simple formula demonstrates that maximal strength, or the capacity to generate significant amounts of force, is essential for power generation and jumping heights. Coaches and scientific researchers are committed to finding effective training methods to improve maximal muscle strength and power, and have found many muscle strength and power training methods. Previous studies proposed that the way to develop power is to develop maximal strength, force rate, ballistic movements, plyometrics and

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technical exercises(Kraemer and Newton, 1994; Bompa, 1999; Zatsiorsky et al., 2020). Therefore, athletes must simultaneously increase their maximal muscle strength and movement speed in order to achieve great power. Complex training (CT), a form of combination training, is best described as training that alternates between traditional RT (heavy RT) and PT (light RT) within a single training session(Chu, 1996; Ebben and Blackard, 1997; Ebben, 2002). CT can increase maximal muscle strength and power at the same time (Carter and Greenwood, 2014; Pagaduan and Pojskic, 2020). Nonetheless, in traditional complex training (TCT), the RT portion of TCT primarily employs weight plates as resistance method, which is affected by the force arm in human biomechanics, i.e., the load that muscles overcome at different joint angles is different, and the maximal load that muscles overcome at the muscle viscoelastic point determines the maximal intensity in the concentric phase of the muscle(Norrbrand et al., 2010), which means that only at the viscoelastic point does the maximal intensity in traditional resistance training (TRT) methods cannot provide adequate load intensity during the eccentric training phase because muscle eccentric contraction produces more force than concentric contraction(Alkner et al., 2003). According to studies, TRT can only provide 40% to 50% of the maximal eccentric load during the eccentric phase (Dudley et al., 1991). In comparison to low-load eccentric training, high-load intensity eccentric training has superior effects on developing muscle strength and hypertrophy(Hakkinen, 1981; Dudley et al., 1991; Norrbrand et al., 2008; Norrbrand et al., 2010; English et al., 2014).

Therefore, new training techniques are continually sought to enhance the capacity of skeletal muscles to develop muscle strength and power (Perez-Gomez and Calbet, 2013). Inertial-resistance training, specifically using flywheel devices, has emerged as an alternative to TRT. The flywheel paradigm offers limitless resistance throughout the entire range of motion (Norrbrand et al., 2008; Norrbrand et al., 2010), which optimizes muscle loading at each joint angle (Tesch et al., 2017). Properly performed flywheel exercise may provide a safer and more effective eccentric phase than TRT (Raya-González et al.; Maroto-Izquierdo et al., 2017b; Tesch et al., 2017; Raya-González et al., 2021), resulting in improved physical capacity and athletic performance-related adaptations (Petré et al., 2018; Beato and Dello Iacono, 2020; Beato et al., 2020; Liu et al., 2020; de Keijzer et al., 2022; Bright et al., 2023). Various studies have demonstrated the superiority of flywheel training over TRT for increasing vertical jumping ability (Maroto-Izquierdo et al., 2017b; Puustinen et al., 2023), stimulating muscle fiber hypertrophy (Norrbrand et al., 2008), and improving post-activation performance (Norrbrand et al., 2010). Overall, flywheel exercise is considered a valid and effective training technique.

Due to the paucity of research in flywheel complex training, which might compensate for the shortcomings of TRT in TCT, this study aimed to compare the effects of an eight-week periodized strength/power training program between flywheel complex training with eccentric-overload (FCTEO) and TCT. Furthermore, to examine the squat jump (SJ), countermovement jump (CMJ), three-step approach jump (AJ), maximal semi-squat strength (1RM-SS), and the muscle thickness at the

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proximal, mid, and distal sections of the quadriceps femoris of well-trained volleyball players.

Methods

Experimental Approach to the Problem

A randomized two-group design with repeated measures was utilized. Sample size was determined using G*Power Software (Faul et al., 2007), with a power of (1-β) .90, an alpha error of .05, and an effect size of .58 based on previous study examining the benefits of flywheel resistance training (FRT) on team sport participants (Seynnes et al., 2007). Thus, a minimum sample size of 12 participants was necessary. Participants (n=14) were then randomly assigned to the FCTEO group, which performed RT with a flywheel device, or the control group (the traditional complex training group, TCT group), which performed RT with a Smith machine. All other training factors (specific training, rest, movement tempo, training attire, food, etc.) remained constant. The training interventions lasted three times each week for eight weeks. Before and after the examination, muscle density, strength, and power were measured (Figure 1).

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Figure 1. Design of the Entire Study, Including All Points of Measurement

Subjects

The study selected 14 women from high level volleyball team, whose competitive level was Division I. Throughout the previous three months, they engaged in volleyball practice at least four times each week, as well as RT and jumping exercises. Fourteen women were assigned randomly to either the FCTEO or TCT group. The ages, heights, and weights of each subject are enumerated in Table 1. Each participant gave written consent to participate in this research, which was approved by the Capital University of Physical Education and Sports's Ethics Council(2021A39).

Before beginning training (pre) and after 8 weeks of training (post) testing was conducted. Regarding the annual periodization, the research was executed during the off-season. The primary exclusion criteria for this study were a lower limb joint injury within 6 months prior to the study and/or a severe lower limb muscle injury (strains lasting more than 27 days) within 2 months prior to the study. (Maroto-Izquierdo et al., 2017a). Athletes who sustained an injury during the study's experimental phase were excluded. No participant was excluded from the research. In addition, during the study, all athletes adhered to consistent dietary regimens that were designed to meet their body weight and activity requirements, Which was recorded by 24-hour quantitative food frequency Questionnaire (Assessment, 2018). Athletes were encouraged to track their sleep habits and it appeared that they consistently received the recommended 8 hours per night. Alcohol consumption was minimal to nonexistent.

Table 1. Information on the Groups' Anthropometry

Measures

A one-week test was followed by a one-week familiarization session. The participants attended the laboratory four times during the initial week: Monday, participants was dedicated to familiarizing with each testing technique. Before any testing, participants completed a 15-minute general warm-up consisting of dynamic stretching, cycling, and rowing, as well as Submaximal familiarization exercises for the assessment exercises. Basic anthropometric measurements, including the subject's weight, age, height, and training history, were taken on Tuesday. Subsequently, ultrasound imaging was utilized to determine muscle thickness (MT). Wednesday, 1RM parallel semi-squat measure. The subjects underwent a progressive resistance loading test for the 1RM parallel semisquat (top of the thigh parallel to the ground). We instructed the participants to descend and rise without halting until the knee and hip joints were fully extended. An optical encoder (ChronoJump Co., Barcelona, Spain) with an accuracy of 1 mm and a sampling rate of 1000 Hz was mounted to the barbell to measure displacement during both the concentric and eccentric phases. To ensure uniformity across trials and between sessions, the knee flexion angle was evaluated via video analysis (Hudl Technique App, Agile Sports Technologies). Participants began the parallel semi-squat at 50% of their 1RM, with the increments for each load determined according to the technique specified by Brown et al (Brown and Weir, 2001). Weekend, muscular power tests include SJ, CMJ, and three-step approach AJ. The participants completed three maximal SJs, CMJs, and three-step approach AJs, with two to three minutes of rest in between.

A week later, the subjects completed a progressive loading test in the parallel semi-squat utilizing a flywheel device (Desmetec Full 11, Italy), beginning with 0.12 $kg \cdot m^2$ moment of inertia. We increased the moment of inertia for the flywheel until the velocity of the flywheel was similar to that caused by the barbell parallel semi-squat using 80% of 1RM intensity. Each repetition consisted of a maximal concentric action accelerating the wheel, followed by an eccentric action decelerating the wheel to a stop at approximately 90° knee flexion (Fernandez-Gonzalo et al., 2014). A washout interval of 48 to 72 hours was permitted. Participants conducted the first experimental session (FCTEO or TCT) at the same time each day, followed by the second experimental session. The assessment days were separated by at least 48 hours of rest to reduce the influence of fatigue on subsequent measurements.

Hypertrophy Testing

Athletes' muscle thickness (MT) measurements were taken. Participants were instructed to fast for 12 hours prior to the test, abstain from consuming alcohol for 24 hours, refrain from vigorous exercise for 24 hours, and urinate immediately before the exam. Ultrasonic imaging was utilized to determine muscle thickness (MT). Ultrasonic has been utilized in various investigations to evaluate hypertrophic changes(Miyatani et al., 2004; Pretorius and Keating, 2008), and has been proven as a good predictor of gross muscular hypertrophy in these muscles (Abe et al., 2000; Nogueira et al., 2009). It has been stated that the reliability and validity of ultrasonography in identifying MT are very good when compared to the "gold standard" magnetic resonance imaging (Reeves et al., 2004). Testing was performed by an experienced technician using a B-mode ultrasound machine (ECO3; Chison

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Medical Imaging, Ltd, Jiangsu, China). The technician, who was not blinded to group assignment, applied a water-soluble transmission gel (Aquasonic 100 ultrasound transmission gel) to each measurement site and then placed a 5 to 10 MHz ultrasound probe perpendicular to the tissue surface without pressing the skin. Images for muscle thickness measures were captured at distances of 25, 50, and 75% between the lateral condyle of the femur and the greater trochanter of the quadriceps femoris (QF25, QF50, and QF75, respectively). To maintain consistency from session to session, sites were measured with a vinyl measuring tape and then marked with a felt pen. During measurements of the quadriceps, participants stood with their legs stretched and relaxed. To prevent training-induced muscle swelling from obscuring the results, pictures were taken 48–72 hours before to the commencement of the study and following the final training session (Ogasawara et al., 2012).

Power Testing

The participants conducted three maximal-effort jumps and submaximal familiarization trials with the assessment jumps, comprising the squat jump (SJ), the counter movement jump (CMJ), and the three-step approach jump (AJ) . The SJ required players to descend to the starting position, with the knee angle reaching 90 degrees, before stabilizing for two to three seconds. The jump was then performed without a counter movement. Participants were instructed to keep their palms on their ipsilateral hip throughout the jump. For the CMJ, participants were instructed to make a rapid countermovement to achieve a 90-degree knee angle and then instantly extend powerfully through the hips, knees, and ankles to leap as high as possible (Kozinc et al., 2022). The AJ involved a three-step approach and counter movement with the legs before the jump(Sattler et al., 2012). In all jumping tests, participants had to land in the same location from which they had taken off to avoid bending their knees and varying their measurements (Markovic et al., 2004). The participants rested for two to three minutes between each trial and varied tests. Smart Jump (Fusion Sport, Coopers Plains, Queensland, Australia) sampler, capable of monitoring 1202 Hz (Street et al., 2001), was used to capture all jumping tests, with the best jumping recorded for analysis.

Maximal Semi-squat Strength Testing

After consuming breakfast and at least 750 ml of liquid, the athletes assembled at 9:00 AM, having been instructed to get at least 8 hours of sleep the night before. Athletes performed a typical warm-up and submaximal familiarization trials with the assessment activities to quantify maximal strength. Due to its well-established effectiveness, the semi-squat exercise was selected for 1RM testing. The athletes executed a controlled semi-squat to just below parallel while being guided by a professional strength-conditioning coach. Utilizing individual records of historical performance, athletes performed 5*50%1RM, 3*60%1RM, and 2*80%1RM, followed by 1*90%1RM, 1*95%1RM, and 1*100%1RM, as measured following Brown et al. If successful at the 1×100% 1RM lift, the athlete continued to increase the weight by 2.5 kg per attempt until failure (Brown and Weir, 2001). The maximal load lifted by each athlete was recorded as their 1RM. A 5-minute rest period was provided between the lifting attempts for passive recovery.

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Experimental Procedures

The exercises semi-squats and drop jumps comprised a complex training regimen for the lower limbs that was done by the participants. The eight-week training program consisted of three weekly sessions separated by at least 48 hours (Norrbrand et al., 2008). Each session consisted of three sets of eight semi-squat repetitions and three sets of twelve drop jump repetitions. Each workout began with a 6-minute cycling warm-up, two sets of 5 bodyweight drop jumps and two sets of 10 non-maximal repetitions of particular semi-squat exercises. The flywheel device (Desmetec Full 11, Italy) employed by the FCTEO group was equipped with an intensity that provided a mean velocity similar to the mean velocity achieved with 80% of the 1RM semi-squat (Figure 2). FCTEO was conducted by the FCTEO group by extending and flexing the knees and hips to accelerate and decelerate flywheels (Fernandez-Gonzalo et al., 2014). Briefly, each repeat involved rotating the wheels with a maximum concentric push on the platform where the feet were positioned. Over the course of the entire concentric exercise, which ranged from 90°of knee flexion to almost full extension, participants were instructed to press with utmost effort. The flywheel strap coiled back at the end of this concentric movement as a result of inertial forces, which started the reversed eccentric movement. Participants were told to resist softly during the 1/3 of the eccentric action, and then to use maximal braking power to stop the movement at around 90° knee flexion (Fernandez-Gonzalo et al., 2014). With this strategy, eccentric overload was produced (Tesch et al., 2004; Norrbrand et al., 2010; Romero-Rodriguez et al., 2011). The TCT team performed a half-squat on the Smith machine. Both groups did the same training volume with a load equivalent to 80% 1RM (Hanson et al., 2007). After finishing the resistance training part, participants conducted drop jumps. Drop jumps were conducted with the height of the boxes beginning from 45 cm at the first week and raised to 60 cm at the eighth week. The participants were asked to rate their felt exertion at the end of each set. Based on earlier study, the number of sets (Timon et al., 2019), and repetitions (Güllich and Schmidtbleicher, 1996; Mihalik et al., 2008) were determined. Rest intervals between sets lasted 60 seconds, while those between exercises lasted 2 minutes (Fleck and Kraemer).

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Figure 2 Experimental design. Min = minutes. 8 + 2 repetitions = 8 maximal repetitions with
2 initial repetitions utilized to initiate the movement.

Statistical Analysis

SPSS version 20.0 (SPSS Inc., IBM, China) was utilized to conduct the statistical analysis. The statistics depicted in tables and graphs are presented as mean ± standard deviation. Using the Shapiro-Wilk, Levene, and Mauchly tests, the variances of the sample data were assessed for normality, homogeneity, and sphericity, respectively. During the pre-test, between-group comparisons were evaluated using univariate analysis of variance (ANOVA), and the effects of the experimental intervention were assessed using a two-way repeated ANOVA (group [FCTEO vs. TCT] time [pre-test vs. post-test 8 weeks]). When an interaction or main effect was found to be statistically significant, post hoc comparisons using the Bonferroni correction were performed to determine mean differences. At P .05, statistical significance was determined. The training's effect size (ES) was estimated using partial eta squared (Cohen, 1965). According to Cohen, ES values of 0.01, 0.06, and 0.14, respectively, represent modest, moderate, and substantial effects.

Results

Participants from both the FCTEO and TCT groups successfully completed all training sessions. After the training sets, the FCTEO and TCT groups reported comparable levels of perceived effort. Prior to the training session, neither FCTEO nor TCT individuals differed in terms of measurable variables (Table 2). Based on diary entries, all experimental subjects with the exception of one followed the FCTEO and TCT training programs as prescribed. Apart for delayed muscular soreness, no adverse effects were observed in the FCTEO and TCT groups during the training intervention.

Table 2 Muscle thickness and Strength and Power Tests before the Training Period

Hypertrophy

The results of muscle thickness of the quadriceps femoris are presented in Figure 3. There was no significant interaction effect between group and time on QF25 ($F_{group\ x\ time}$ = .015, P = .0908, ES = .002). The main effects of time (F_{time} = .038, P = .852, ES =.006) and group (F_{group} = .015, P = .0908, ES = .002) on QF25 were also not significant. The interaction effect between group and time on QF50 was not significant ($F_{group\ x\ time}$ = .068, P = .802, ES = .011), nor was the main effect of group (F_{group} = 1.145, P = .326, ES = .160). However, the main effect of time on QF50 was significant (F_{time} = 9.145, P = .023, ES = .604), indicating that only the FCTEO participants significantly increased their muscle thickness of QF50 after the training period (p = .048, ES = .504). No significant main effects of group, time, or group x time on QF75 were observed (F_{group} = 1.649, P = .246, ES = .216; F_{time} = .035, P = .858, ES = .006；$F_{group\ x\ time}$ = .001, P = .974, ES = .000; respectively).

Figure 3 QF thickness at proximal (25%), medial (50%), and distal (75%) measurements pre-test and post-test for both, FCTEO and TCT groups. * Significantly different from pre-test value, where *p < .05, Significantly different from pre-test value. QF：quadriceps femoris.

Maximal Semi-squat Strength

The results of maximal semi-squat strength are presented in Figure 4. A significant main effect was observed for time (F_{time} = 28.672, P = .002, ES = .827) and group x time ($F_{group\ x\ time}$ = 6.080, P = .049, ES = .503). Both the FCTEO and TCT groups showed a significant increase in 1RM semi-squat value after the training period ($F_{FCTEO\ group}$= 45.950, P = .001, ES = .885; $F_{TCT\ group}$ = 7.886, P = .031, ES = .568, respectively). Post-hoc analysis revealed that the FCTEO group had a significantly higher 1RM semi-squat value than the TCT group (p = .021, ES= .671). There was no significant main effect observed for the group (F_{group} = 2.819, P = .144, ES = .320).

Figure 4 1RM semi-squat measurements pre-test and post-test for both, FCTEO and TCT groups. * Significantly different from pre-test value, where *p < .05, **p < .01, #Significantly different between FCTEO and TCT groups after the training program, where $^{\#}$p < .05.

Power

Power results are presented in Figure 5.

SJ

No significant main effects of group or group x time on SJ height were found (F_{group} = 2.567, P = .160, ES = .300; $F_{group\ x\ time}$ = 3.441, P = .113, ES = .364, respectively). However, the main effect of time had a significant main effect on SJ height (F_{time} = 10.451, P = .018, ES = .635). Post-hoc analysis indicated that TCT participants significantly increased SJ height compared to FCTEO participants after the training period ($F_{TCT\ vs.\ FCTEO}$ = 11.131, P = .016, ES = .650). The main effects of group and time on SJ peak power were significant (F_{group} = 7.103, P = .037, ES = .542, and F_{time} = 6.968, P = .039, ES = .537, respectively). The post-hoc analysis showed that TCT participants had significantly higher SJ peak power than FCTEO participants after the training period ($F_{TCT\ vs.\ FCTEO}$ = 6.972, P = .039, ES = .537). Thus, compared to the FCTEO training program, the TCT training program was better at increasing the SJ height and peak power in well-trained volleyball players.

CMJ

Significant main effects of group and time on CMJ height were found (F_{group} = 6.547, P = .043, ES = .522, and F_{time} = 18.968, P = .005, ES = .760, respectively). Post-hoc analysis showed that FCTEO participants had significantly higher CMJ height than TCT participants ($F_{FCTEO\ vs.\ TCT}$ = 11.060, P = .016, ES = .648) after the training period. Significant main effects of time and group x time were also found on CMJ peak power (F_{time} = 9.161, P = .023, ES = .604, and $F_{group\ x\ time}$ = 7.597, P = .033, ES = .599, respectively), with FCTEO participants having significantly higher CMJ peak power than TCT participants ($F_{FCTEO\ vs.\ TCT}$ = 17.952, P = .005, ES = .750) after the training period. No significant main effects of the group on CMJ peak power were observed. Therefore, the FCTEO training program was better than TCT in increasing CMJ height and peak power in well-trained volleyball players.

AJ

Significant main effects of group and time on AJ height were found (F_{group} = 8.246, P = .028, ES = .579, and F_{time} = 20.851, P = .004, ES = .777, respectively). The interaction effect of group x time on AJ height was not significant ($F_{group\ x\ time}$ = .884, P = .383, ES = .128). Post-hoc analysis revealed that FCTEO participants had significantly higher AJ height than TCT participants ($F_{FCTEO\ vs\ TCT}$ = 6.974, P = .038, ES = .538) after the training period. The study also found a significant main effect of time on AJ peak power (F_{time} = 11.270, P = .015, ES = .653), with only FCTEO participants showing a significant increase in AJ peak power ($F_{FCTEO\ group}$ = 10.813, P = .017, ES = .643). Although no significant main effects of group and group x time on CMJ peak power were found, the increase in AJ peak power after FCTEO training was partially more significant than that of TCT intervention ($F_{FCTEO\ vs.\ TCT}$ = 5.705, P

= .054, ES = .478). Therefore, the FCTEO training program appeared to be more effective than TCT in increasing AJ height and peak power in well-trained volleyball players.

Figure 5 Power measurements pre-test and post-test for both, FCTEO and TCT groups. * Significantly different from pre-test value, where *p < .05, **p < .01, #Significantly different between FCTEO and TCT groups after the training program, where #p < .05.

Discussion

According to the authors, this is the first study to compare the muscular adaptations of elite volleyball players trained with FCTEO versus TCT. The results of this study indicated that more significant increases in muscle thickness, strength, and performance in CMJ and AJ were achieved after an 8-week training program comprising flywheel complex training as part of a competitive volleyball training regimen than traditional complex training. Nevertheless, a significant improvement in SJ was only observed after TCT.

Muscle Hypertrophy

Our results showed that only the FCTEO group significantly improved muscle thickness at the midpoint of the quadriceps femoris (50% QF) post-training. Although there was no significant difference between the FCTEO and TCT groups, 50% of the QF muscle thickness in the FCTEO group (6.0%) increased by twofold greater than that in the TCT group (3.0%), which is similar to previous studies. A study from Norrbrand et al. found quadriceps muscle volume increased by 6.2% following 5 weeks of FRT, twofold greater than that shown in traditional resistance training (3.0%), but there was no significant difference between groups (Norrbrand et al., 2008). Similar increases were also found in healthy men and women after flywheel resistance training, such as a 5% increase in leg muscle mass (Fernandez-Gonzalo et al., 2014), a 7% increase in CSA (cross-sectional area) (Seynnes et al., 2007), and an 11.4% increase in rectus femoris muscle thickness (Horwath et al., 2019). Consequently, it seems FRT shows great potential for improving muscular hypertrophy compared to TRT.

Only the FCTEO group improved muscle thickness at the midpoint of the quadriceps femoris (50% QF) with flywheel training in our study. On the one hand, flywheel semi-squat training had greater use on the rectus femoris of the quadriceps (Illera-Domínguez et al., 2018; Kubo et al., 2019). A study has shown greater exercise-induced contrast shift and increased transverse relaxation time (T2), a tool used in MRI to quantify muscle use during exercise and to predict the magnitude of increase in CSA, following flywheel semi-squats compared with barbell squats. Furthermore, the rectus femoris increased T2 more with the flywheel semi-squat (+24 ± 14%) than with barbell squats (+8 ± 4%) (Norrbrand et al., 2011). On the other hand, there is evidence that eccentric activities cause greater myofibrillar disruption and muscle damage than concentric actions (Friden and Lieber, 1992; Gibala et al., 1995). It is believed that muscle injury generated by such loading is a crucial stimulus

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for myofibrillar remodeling and consequently muscular growth (Evans and Cannon, 1991; Yu et al., 2003).

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Maximal Muscle Strength

The present results demonstrated that FCTEO training was more effective at improving strength in the semi-squat than TCT training (p =.021, ES =.671), increasing strength by 22.5% (FCTEO group) and 12.4% (TCT group), respectively, which is similar to Fernandez-Gonzalo et al., who found a 6 weeks of training on a flywheel squat device without a control group resulted in a 25% and 20% increase in 1 RM for men and women, respectively. (Fernandez-Gonzalo et al., 2014). In contrast to our results, Maroto-Izquierdo et al. found no significant differences in the increase of the 1RM leg press in well-trained handball players between a FRT and a TRT program (Maroto-Izquierdo et al., 2017a). The contrary result could be due to the training duration and sessions. since longer training duration and more training sessions have a larger impact on resistance training adaptations (Moran et al., 2017). In our study, the training intervention lasted 8 weeks or 24 sessions in total. While in the study of Maroto-Izquierdo et al., the training intervention only lasted six weeks or 15 sessions.

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Additionally, FRT in the FCTEO group used in our study is indeed very different from the traditional resistance training in the TCT group. During flywheel exercise, the rotational inertia generates a larger eccentric overload than TRT.(Maroto-Izquierdo et al., 2017b). Moreover, TRT at varying intensities was constant resistance training. Flywheel, on the other hand, offered unrestricted resistance at all intensities and maximal or nearly maximal activation from the start due to its inertia force(McErlain-Naylor and Beato, 2021). As exercise intensity has been recognized as a significant determinant of strength training-induced adaptations(Campos et al., 2002; Heggelund et al., 2013). Additionally, eccentric loading led to certain neuromuscular changes such attenuated motor recruitment(Douglas et al., 2017), preferential recruitment of high threshold motor units, and increased cortical activity (Hody et al., 2019). Lastly, it has been shown that a rise in the production of the eccentric phase force is followed by an increase in the output of the concentric phase force (Takarada et al., 1997; Doan et al., 2002).Together, these physiological distinctions support our study findings and the usefulness of flywheel training in enhancing volleyball female players' strength.

Muscle Power

The results of CMJ in this study are comparable to those of prior research. A study of elite soccer or basketball players found that flywheel resistance training led to significant increase in CMJ height (Seynnes et al., 2007; Stojanović et al., 2021). While a research of physical education students did not elicit substantial increases in SJ or CMJ, this may be due to the elite level of our participants. Indeed, training age (Till et al., 2017), and strength level (Prue et al., 2010) have been found to influence changes in power after resistance training. However, FCTEO participants had no significant effect on SJ performance, which may result from the less intense stimulation of concentric muscle contraction caused by the flywheel compared with TCT (MacDougall et al., 2014).

Furthermore, the large improvements in power tests (CMJ, and AJ) in FCTEO training groups may be caused by the increased semi-muscle strength. As the FCTEO training technique is similar to the CMJ test technique, the increased semi-muscle strength transfer to CMJ after FCTEO training is relatively easy to achieve. And post-activation performance enhancement (PAPE) may also play an important role in improving power. Since a positive PAPE effect caused by flywheel resistance training on the jumping performance has been reported (Beato et al., 2019; Timon et al., 2019; Maroto-Izquierdo et al., 2020; Beato et al., 2021a; Beato et al., 2021b).

In addition, increased muscle-tendon stiffness may have contributed to the improvements in CMJ and AJ in the FCTEO training group. That impact of inertial training was noticed by Onambele et al. (Onambélé et al., 2008), who found a 136% rise in gastrocnemius lateralis and soleus tendon stiffness after 12 weeks of inertial training in senior volunteers. It may also be brought on by an improvement in the stretch-shortening cycle (SSC) (Bosco et al., 1981), and an increase in the excitability threshold of the Golgi tendon organs (McNeely and Sandler, 2006). We did not, however, measure these variables. Changes in neuromuscular coordination can also influence post-exercise power gains. During EMG measurements, neuromuscular control can be seen to improve(Tesch et al., 2004) ,and Seynees et al. (Seynnes et al., 2007) assessed changes in EMG signals after training.

Some restrictions demand additional consideration. Due to the degree of competition of our data, the results can only be generalized to similar degree of competition. Due to the off-season nature of the training intervention, it was outside the scope of this study to explore the effects of FCTEO on field-based performance measures such as sprint speed and COD. Nonetheless, such measurements could have offered further information regarding the transfer of FCTEO to team sport tasks, as FRT has been demonstrated to result in larger increases in speed and COD than TRT (Maroto-Izquierdo et al., 2017b). Since the focus of our study was on the lower body, future research should also evaluate the effects of FCTEO on the upper body. This may have substantial performance and injury prevention implications for volleyball players, as the upper body is heavily involved in training and competition (spiking, serving, blocking) (Sheppard et al., 2007). Despite this limitation, a better efficacy was reported for FCTEO training. Future research should investigate monitoring surface electromyography in the application of FCTEO, it is suggested.

Conclusions

FCTEO training is better to improve muscular adaptation in a way in elite female volleyball players. These findings have significant implications for professionals who work with elite female volleyball players. Given the importance of increasing muscle thickness, strength, and power in female volleyball players, the training interventions presented here provide advise on the FCTEO approach that can be used to improve these characteristics. Despite the fact that our findings suggested that FCTEO may be superior to TCT, FCTEO is a good training strategy for enhancing lower-body muscular thickness, strength, and power. Future study examining FCTEO in female athletes should investigate the effects of various training prescription variables (e.g., intensity, volume, and frequency) on optimizing strength, power, and speed.

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