

THESIS

STRENGTH AND POWER THROUGHOUT THE MENSTRUAL CYCLE

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ABSTRACT

STRENGTH AND POWER THROUGHOUT THE MENSTRUAL CYCLE

Purpose: The purpose was to determine if maximal muscle performance varies across the menstrual cycle because historically this measurement has been left out of research and women report feeling differences between phases. Strength and ballistic force production were measured in normally cycling eumenorrheic women and in women on hormonal birth control. We expected greater performance during the follicular vs. luteal phase because of fluctuating hormones, specifically estrogen, for the normally cycling women and more constant values for women on birth control because of the lack of fluctuating hormones due to effects of birth control.

Methods: Participants were physically active women between 18-40 years who were either 1) eumenorrheic and not taking hormonal birth control (N=13), or 2) taking birth control (N=10). Ovulation was determined via body temperature and LH strips, and along with menses, was tracked for one full cycle prior to strength testing as well as during their two months of strength testing. Identical assessments were performed on four visits in the luteal and follicular phases over two consecutive months of menstrual cycles. Tests included leg and arm strength, ballistic force production, and vertical jump.

Results: Comparisons were made between the luteal and follicular phases within subjects and between the normally cycling and hormonal birth control groups. No significant differences were found in for strength or ballistic functional measures between menstrual phases or between the groups ($p > 0.05$).

Conclusions: Meaningful differences between phases would suggest that hormonal fluctuations affect muscle performance. We found no difference in muscle function between follicular and luteal phases. This suggests that the hormonal variation during the menstrual cycle is insufficient to alter maximal neuromuscular output. One possibility is that the relatively low number of participants hampered the ability to detect differences. If there are no differences between phases, the female athlete does not need to adjust their training and competition schedules.

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1. INTRODUCTION

Considering the recent federal movement (Mazure & Jones, 2015) for the equal inclusion of females and males in research studies, a clearer understanding is needed of the potential influence of menstrual phases on various aspects of physiological function. Historically, studies have often excluded women out of convenience and therefore some important clinical findings do not account for responses in women (Mazure & Jones, 2015). In the case of disease diagnosis and treatment, this practice could be detrimental to the health of women.

A more complete understanding in this area should aid in the interpretation of sex-based differences in future studies. For example, in the context of neuromuscular performance outcomes such as muscle strength (Mazure & Jones, 2015), knowledge of the impact of menstrual cycle on the expression of strength would enable designers of research studies to time data collection appropriately.

Furthermore, in the strength and conditioning realm, application of evidence-based training programs to female athletes based on results from men could be less effective due to sex differences in endocrine responses underlying muscle adaptation and physiological mechanisms that benefit athletic performance (Chilibeck, Calder, Sale, & Webber, 1998). A more complete understanding of how fluctuations in female sex hormones affect performance would allow athletes and coaches to use this knowledge to optimize training programs.

Numerous studies have shown that women exhibit greater muscle strength during the follicular phase of the menstrual cycle compared with the luteal phase (Hudgens, 1988; Sarwar, 1996; Sung, 2014; Mohamed, 2000; Phillips, 1996; Chilibeck, Calder, Sale, & Webber, 1998) . This trend has been observed in a variety of muscles using a variety testing protocols; however,

the physiological mechanisms that underlie the differences across menstrual phases are not completely understood. Strength output involves a contribution from both the nervous system activation and muscle contractile function (Mohamed & Abdel-Rahman, 2000). Likewise, menstrual cycle-based differences in strength have been attributed to the acute effects of increased estrogen on both muscle contraction (Mohamed, 2000) and neuromuscular activation (McEwen, 1999). Estrogen has been found to be excitatory to the central nervous system (CNS) (Mohamed & Abdel-Rahman, 2000) and trophic to muscle (McEwen & Alves, 1999), in contrast to progesterone, which can inhibit nervous system function in part to the influence on GABA (gamma-Aminobutyric acid is the main inhibitory neurotransmitter in the CNS) function in the CNS (McEwen & Alves, 1999) and may contribute to muscle dysfunction (McEwen & Alves, 1999). This is thought to be the primary notion underlying the greater strength and performance during the follicular phase when estrogen is high and progesterone is low, compared with the luteal phase when estrogen is lower, and progesterone is relatively higher.

That said, the current body of literature on this question is not conclusive, and furthermore is lacking an explanation of the mechanism of this effect. Some of the studies that have compared strength performance between the two phases show a significant difference (Hudgens, 1988; Sarwar, 1996; Sung, 2014; Mohamed, 2000; Phillips, 1996; Chilibeck et al., 1998) and some do not (Slauterbeck, 2002; Janse de Jonge, 2003; Elliott, 2005; Janse de Jonge, 2001). Furthermore, there has been no research on menstrual cycle-related differences in explosive, ballistic force production, whether in isolated muscle testing or explosive whole-body movements. For many athletes, an important underlying feature of performance is their ability to produce muscle force rapidly and exert powerful movements (Iguchi et al., 2011).

Given the potential influence of hormonal fluctuations on nervous system and muscle function, the purpose of this study was to determine if muscle strength and ballistic performance vary significantly across the phases of the menstrual cycle. Strength and ballistic force production were measured in eumenorrheic women with ostensibly normal hormonal fluctuations and in women taking hormonal birth control. The expectation was that performance would be greater in the follicular vs. Luteal phase for the normally cycling women and be more constant for women on birth control (Elliott, Cable, & Reilly, 2005).

1. LITERATURE REVIEW

It is now somewhat appreciated that human research studies should include both sexes when appropriate (Mazure, 2015). Failing to do so generally decreases the quality and applicability of information gained, interferes with meaningful interpretation of the efficacy of clinical or exercise interventions, and could unintentionally reinforce negative sex-based stereotypes and create inequities in health outcomes (Mazure, 2015). More needs to be done to clear up conflicting outcomes and address the lack of data surrounding women's health research (Mazure, 2015).

Athletic performance in female athletes

Recent research is conflicting on how sex hormones may affect the performance of female athletes. Overall, the exact mechanism that explains this effect is not entirely understood. The purpose of a recent paper by McEwen et al. was to tackle the complexity of the integration of the endocrine system and the nervous system (McEwen, 1999). They did this by exploring how fluctuations associated with the menstrual cycle can modify the motor nervous system in vivo and how the menstrual cycle could influence motor behavior (McEwen, 1999).

Sex hormones, and their precursors and metabolites, have been shown to have a profound effect on the nervous system. They can be either excitatory or inhibitory to the nervous system. For example, pregnenolone, a progesterone precursor, has been shown to increase the inhibitory effect of GABA and produce an inhibitory effect on the nervous system (Schultz, 2009).

In addition, estrogen, specifically estradiol, plays a large role in the maintenance of the central nervous system. It appears to play a role in the development and trophism of the nervous

system and has a net excitatory/trophic effect. Recent work in rodents has indicated that estrogen receptors on GABA releasing (GABAergic) neurons may be the primary way in which estradiol creates a net excitatory effect on the nervous system (Schultz, 2009). Activation of estrogen receptor α on GABAergic neurons attenuates the release of GABA. This mechanism explains how estradiol rapidly affects neurotransmitter pathways for both dopamine (Becker, 1990) and glutamate (Smith, Waterhouse, Chapin, & Woodward, 1987) in rodent models. This excitatory effect has been shown in vivo whereby estradiol administration increases neuronal discharge of the rat cerebellum during treadmill walking (Smith, Waterhouse, & Woodward, 1988). This mechanism explains how estradiol rapidly affects neurotransmitter pathways for dopamine and glutamate. This increase in neuronal discharge during treadmill walking has been shown in rodent models (Smith, 1988).

The role of estrogen has been studied using different methods. First, via direct nervous system stimulation techniques, and second, by recording single motor unit activity during voluntary contractions. Early research has shown that the amplitude of H-reflexes elicited by stimulation of the peripheral nerve does not change during the menstrual cycle, however the corticospinal tract excitability is highest and inhibition lowest in the late follicular phase compared to early follicular or mid-luteal (Smith, 1988). Altogether, the stimulation research suggests that the function of the descending motor tracts is altered during the menstrual cycle and may be facilitated in the late follicular phase.

Neurological function related to sex hormones was tested by using a hand steadiness assessment between men and women. They did this in two different experiments including 58 men, 19 women taking hormonal birth control, and 48 normally cycling women, ages 18-32 years. In the first study they were tested for their ability to hold a stylus in a series of

holes without touching the hole. They found the normally cycling women were steadier than the men in the follicular phase, but the women on hormonal birth control had significantly less hand steadiness overall. The normally cycling women, however, showed significant performance changes associated with cycle phases, performing the best in the follicular phase and worse in the luteal phase. All subjects performed better with their dominant hand. For the second part of the experiment, five women taking oral contraceptives and seven normally cycling women were tested with dummy pistols weighted to simulate medium and large caliber revolvers. Each weighted handgun was tested in a supported and unsupported testing position. The normally cycling women made fewer aiming errors compared with the women on oral contraceptives. However, the performance of the normally cycling women was significantly impaired during the week prior to menses. The steadiness advantage of the normally cycling women was similar for the different pistol weights (Hudgens, Fatkin, Billingsley, & Mazurczak, 1988).

Sports medicine professionals typically describe two functionally different units of the vastus medialis (VM) and the vastus medialis oblique (VMO), despite there being no differences anatomically. Griffin et al. sought to determine if the motor units of the VM and VMO are recruited differently due to sex hormones and the different phases of the menstrual cycle (Tenan, Peng, Hackney, & Griffin, 2013). They measured single motor unit recordings from each muscle in men and women from the isometric knee extension measurement. They measured 11 men at one time point and seven women were tested at five different time points during the menstrual cycle. They found that the initial firing of the VMO compared to the VM fluctuated in women but not in men. They found that in women, initial firing rate in the VM was higher in the early follicular to late luteal phase and the VMO was lower in initial firing rate than the VM during ovulation and midluteal phases. They concluded that the control of the VM and VMO change

across the menstrual cycle and could contribute to the greater incidence of knee injuries in women compared to men (Tenan et al., 2013)

Relating psychological factors and perception of effort to performance might better explain the differences found throughout the menstrual cycle (Simic, Tokic, & Pericic, 2010). For example, Simic et al. assessed the effects of the menstrual cycle on motor and spatial tasks, anxiety, and perceived exertion. They tested 20 participants, ages 18 to 21 years, with a regular menstrual cycle. The participants performed a finger dexterity test and mental rotation test during menstruation, late follicular, and the midluteal phase. Before each test, they were given the anxiety questionnaire and rate of perceived exertion was measured via the Borg scale. The results showed the best performance in both tests in the midluteal phase, when both estrogen and progesterone are relatively elevated. The anxiety level and task difficulty ranking were the highest in the early follicular phase, when the hormone levels were the lowest (Simic et al., 2010).

Effect of estrogen on skeletal muscle

Less is understood about the acute effects of estrogen on muscle function compared with the chronic effects. For example, estrogen is known to provide a chronic protective and trophic effect on skeletal muscle (Prochniewicz et al., 2008). After menopause, women experience a decline in skeletal muscle mass which has been linked to the dramatic post-menopausal decrease in estrogen levels (Prochniewicz et al., 2008). Recently, electron paramagnetic resonance (EPR) spectroscopy was used to directly investigate the trophic effects of estradiol on myosin in muscles of female mice. They discovered several acute effects of removing estrogen in these mice. The implications of the findings were three-fold. First, after the removal of estrogen they

found a reduced function in myosin along with a reduction of specific force (force per unit mass). They then returned estrogen levels to normal with estrogen treatments and the reductions were reversed. They found the reduction was due to structural changes in the myosin head specifically (Wattanapermpool, Riabroy, & Preawnim, 2000). Second, they concluded that estrogen is a very important hormone that affects force generation at a molecular level. Last, myosin was specifically identified as a contractile protein detrimentally affected by reduced estradiol levels (Moran, 2007).

Strength during the menstrual cycle

Healthy eumenorrheic women who are not taking hormonal birth control should have fluctuating highs and lows of progesterone and estrogen during the menstrual cycle. The relevant question here is how this affects performance outcomes such as maximal force. One study examined muscle strength and the rate of fatigue between phases of the menstrual cycle in 100 healthy women ages 18-24 years (Pallavi, UJ, & Shivaprakash, 2017). Strength and fatigue rate were assessed using a handgrip dynamometer. They found that handgrip strength was 20% higher in the follicular phase (higher estrogen and low progesterone) compared with the luteal phase (lower estrogen and high progesterone) (Pallavi, 2017).

In contrast, Dr. Janse de Jonge, a prominent researcher in this area, has found that strength and endurance performance are not affected by female sex hormones. Her research suggests that oxygen consumption, heart rate, and responses to submaximal steady state exercise are not affected by the menstrual cycle and that women do not need to adjust their training or competition schedule around their cycle phases (Janse de Jonge, 2003). Dr. de Jonge's group tested the influence of the different phases of the menstrual cycle specifically on the contractile

characteristics of skeletal muscle. They looked at both phases and measured maximal isometric quadriceps strength and fatigability, electrically stimulated contractile properties of the knee extensors, and handgrip strength. They found no significant differences between the two phases of the cycle and concluded that the cycle-related fluctuations in sex hormones do not affect muscle contractile characteristics.

In contrast, one of the first studies on strength and menstrual cycle assessed differences in muscle strength between the luteal and follicular phases and compared women on hormonal birth control to women not taking birth control. The eumenorrheic group (N = 10) exhibited 11% greater handgrip and quadriceps strength in the follicular compared with the luteal phase. The hormonal birth control group (N=10) was used as a control group and they were found to have no differences in strength across the menstrual cycle compared to the eumenorrheic group (Sarwar, Niclos, & Rutherford, 1996).

Muscle strength of the adductor pollicis (AP) was studied throughout the menstrual cycle to determine whether any variation in force is associated with the known cyclical changes in ovarian hormones (Phillips, Sanderson, Birch, Bruce, & Woledge, 1996). Three groups of young women were studied: regularly menstruating trained (N=10), and untrained (N=12) and trained hormonal birth control users (N=5). They had one control group of untrained men (n =10). The trained women were competition rowers. They measured maximum voluntary force (MVF) of AP which measured over a period of 6 months. The trained women were measured three times a week before practice and the untrained women tested eight different times to still get the same amount of testing done but since they don't have practice, they mimicked the amount and time of testing as the training group. Ovulation was detected by luteinizing hormone measurements or change in basal body temperature. Their results showed a significant 10% increase in MVF

during the early follicular phase of the menstrual cycle when estrogen levels are rising, in both the trained and untrained groups. This was followed by a similar drop in MVF around the time of ovulation when estrogen is at its peak. Neither the hormonal birth control group nor the male subjects showed cyclical changes in MVF (Phillips, 1996).

In this area of investigation many researchers have focused on the female menstrual cycle in relation to strength. The concern for some investigators is related to fluctuating hormone levels, strength, and joint ligament laxity as a contributor to greater ligament injury rates. One study sought to test if the ACL define injuries occur randomly or were more prevalent during specific phases of the menstrual cycle (Slauterbeck et al., 2002) Researchers asked athletes to complete a post-knee injury questionnaire that determined the timing of their last menstrual cycle and if they were on birth control or not. Each subject provided a saliva sample to determine their progesterone and estrogen levels at the time of the questionnaire to determine the timing of their cycle relative to the time of injury. They did this to correlate actual hormone levels with the self-report of menses at the time of injury. Ten out of 27 athletes sustained an ACL injury immediately before or one to two days after their menses. They determined that the increase in injury rate on days one and two of the menstrual cycle was greater than random chance (Slauterbeck, 2002).

It is important not only to understand what a single strength test or maximal output looks like between phases, but to also understand on a daily, monthly, and yearly basis how hormones affect training, competition, and practice. One study examined hormone fluctuations in the menstrual cycle and how it affects strength training and muscle building during strength training workouts (Sung et al., 2014). The women in this intervention study were placed into two groups. one group performed eight sessions of leg press training during their luteal phase and two

sessions during their follicular phase, and the other group performed the opposite pattern of training between phases. The researchers found that the participants who did most of their leg press sessions in the follicular phase increased type 1 and type 2 muscle fiber size. They also increased their maximum isometric force from single fibers (f-max), and the single fiber diameter as measured by real time ultrasound imaging and had alterations in estrogen and progesterone; both progesterone and estrogen levels overall decreased at the end of the intervention. In contrast, the other group, who did the majority of their leg press sessions in the luteal phase, experienced no alterations muscle fiber type, size, hormone levels, f-max, or fiber diameter from pre- to post-test. They demonstrated that follicular phase-based strength training induces significantly greater effects on strength and muscle and that a periodized program based around their menstrual cycle would be beneficial for performance (Sung, 2014).

Hormonal Birth Control and Exercise

Despite the minimal research on women taking hormonal birth control, it is generally understood that for women on birth control, performance and hormone changes are far different compared with women not on birth control (Elliott et al., 2005). Women on hormonal birth control do not have the same hormonal fluctuations as a eumenorrheic woman and therefore do not have a normal menstrual cycle including ovulation and menses (Elliott, 2005). Hormonal birth control is typically administered in three different forms (monophasic, biphasic or triphasic) that differ widely in how they affect the body (Elliott et al., 2005). Therefore, the outcomes of performance measures for women on hormonal birth control might be expected to vary. Since fluctuations in sex steroids are believed to be a possible factor in performance and exercise capacity, it is important to understand the effect of administering various types of hormonal birth

control to women. However, the research into oral contraceptives and exercise performance is not consistent.

The type of hormonal birth control administered (monophasic, biphasic or triphasic), as well as the type and dose of estrogen and progesterone may have varying effects on exercise performance (Elliott, 2005). To date, research in the area of oral contraceptives and exercise capacity is sparse and muddled by poor research design, methodology and small sample size (Elliott, 2005). It is clear from the research to date that more information is needed on the array of types of birth control in women's health generally and specifically on exercise performance (Elliott, 2005).

One such study examined the effects of oral contraceptive use on maximal force production in young women (Burrows, 2007). They studied two groups with a total of 21 female participants (14 on hormonal birth control and seven eumenorrhic controls). All participants taking birth control had been taking a combined, monophasic oral contraceptive pill for at least six months. Maximum dynamic and isometric leg strength, maximum isometric strength of the first dorsal interosseus (FDI) muscle, and plasma concentrations of estrogen and progesterone were measured on days seven and 14 of pill consumption and day five of pill withdrawal. The eumenorrhic group was tested on days two and 21 of the menstrual cycle. They concluded that there were no significant changes in muscle strength between test day two (follicular phase) and 21 (the luteal phase) for either of the groups. They also found the hormonal birth control group did not significantly differ from the eumenorrhic group, even though the eumenorrhic group had significant fluctuations in estrogen and progesterone throughout their menstrual cycle compared with the lack of fluctuations with the hormonal birth control group. Altogether,

hormonal birth control users were similar compared with eumenorrheic women not taking hormonal birth control on measures of muscle strength (Burrows, 2007).

Although the effects of exogenous estrogen and progesterone on muscle strength has not been completely determined there have been mechanisms suggested through which hormonal birth control may enhance athletic performance, 1) increasing growth hormone levels in response to exercise, thereby attenuating delayed-onset muscle soreness, and 2) reducing the incidence of injuries by reducing fatigue caused by premenstrual syndrome (Nichols, 2008). Previous studies suggest that the use of monophasic, combination hormonal birth control does not significantly affect peak torque or isometric strength (Nichols, 2008). For example, Nicholas et al. found that the use of combination hormonal birth control has no effect on maximal force production measured by adductor pollicis longus maximum voluntary contraction, knee extension/flexion peak torque, and forearm isometric endurance (Nichols, 2008). This study was designed to investigate the effects of combination birth control on strength in collegiate softball and water polo female athletes. The athletes participated in a 12-week strength development program. A double-blind research design was used to mask subjects to the main outcome of interest, strength gain differences between groups. The researchers were blinded to the hormonal birth control use of participants until data collection was completed. They studied two groups including 13 birth control users and 18 eumenorrheic women not taking any form of birth control. All subjects participated in the same supervised 12-week pre-season strength development program. Their strength tests at weeks 0 (pre-test), 4, 8, and 12 (post-test) included one-repetition maximum bench press (1RMBP), 10-repetition maximum knee extension (10RMLE), isokinetic peak torque bench press (IKBP), and isokinetic peak torque knee extension (IPKE). They found a significant increase in strength over the course of the 12-week study which was found

consistently between both groups for all tests. No significant differences in IKBP torque production occurred during the 12-week strength training program. No significant differences pre and post-test over the 12-week strength training program in 1RMBP, 10RMLE, IKBP, or IKLE occurred between the birth control group and non-birth control group. They concluded that the use of combination birth control did not provide an androgenic effect sufficient to increase strength gains more than the stimulus from the training protocol (Nichols, 2008).

Ballistic muscle performance across the menstrual cycle

Maximal muscle force (muscle strength), considered above, is an important and well-characterized feature of muscle function (Aagaard, 2002). It is also important to consider the speed of muscle contraction, or rate of force development (RFD) (Aagaard, 2002). However, to our knowledge no studies have examined this functionally important outcome with regard to the female menstrual cycle. What is known is that in vivo estrogen has an excitatory effect on the central nervous system and that progesterone has an inhibitory effect (Smith et al., 1987), which suggests a possible impact on explosiveness as measured by the rate of force development. One study tested and validated the methods necessary to measure and analyze RFD and efferent neuromuscular drive of human skeletal muscle after heavy resistance strength training. This training induced gain in explosive muscle strength could be explained by increases in efferent neural drive, as evidenced by marked elevations in EMG signal in the early phase of muscle contraction (Aagaard, 2002). Altogether, the notion that estrogen has an excitatory effect on the central nervous system suggests that RFD could be different between the follicular and luteal phases.

Summary

Overall, in the current literature, the results and outcomes are conflicting. First, research does show in mouse models and in vivo, that there are hormonal effects of estrogen and progesterone at the cellular level in skeletal muscle and in the nervous system. However not all research consistently reflects that at the level of functional or performance outcomes. There are a few studies that display differences between phases of the menstrual cycle, and there are those that failed to find differences. There are inconsistencies in the way that researchers have measured hormone levels and ovulation, which may be part of the reason for inconsistency of results on menstrual phase and muscle strength. Rate of force development is typically used as a measure of power output and athletic performance but has never been measured in respect to the phases of the menstrual cycle. Theoretically, there could be differences due to the neurological effects of estrogen and progesterone.

It is also clear that the production of sex hormones from reproductive organs may only account for a small change in the level of hormones in the nervous system (Mazure & Jones, 2015). Moreover, the amount of sex hormones in nervous tissue is not uniformly distributed, and it is unknown how menstrual cycle irregularities and hormonal contraception affect the nervous system. With that, it is possible that sex hormones may substantially increase or decrease human performance but is difficult and complicated to capture the effects in athletic performance or rehabilitation gains in humans. The intra-individual variability is complex, and it is difficult to control other contributing factors such as training level, specific sport, nutrition, sleep, mental focus and their interaction with nervous system function. The effect of hormonal variations on rate of force development measures remains poorly described (Mazure, 2015).

2. METHODS

3.1 Participants

Female participants between 18-40 years of age were recruited via word of mouth and advertisements posted in local exercise facilities. They provided written informed consent after screening and orientation to the procedures. The experimental protocol was approved by the Human Research Committee at Colorado State University.

During the initial phone screening and in the subsequent questionnaire, subjects reported regular participation, moderate to vigorous levels of physical activity that specifically includes regular strength training. This was defined as a minimum of two strength training sessions per week on a consistent basis for at least a year. Each participant reported their strength training to be 4-6 days per week on average at a moderate to high intensity. All women in the eumenorrheic (EUM) group reported normal menstrual cycles for at least one year and had not taken hormonal birth control for at least six months prior to the study. One of the eumenorrheic participants was using a non-hormonal IUD. The hormonal birth control group has been on birth control for at least six months. Five of the participants were on monophasic birth control, two were on biphasic and three were using hormonal IUD's. Participants in both groups reported no major health problems, nor neurological or muscle disease.

3.2 Menstrual Cycle Tracking

For each subject, participation and testing schedules were staggered according to the timing of entry into the study. Participation in the study took place over the course of three consecutive months. After entry into the study and prior to testing, on the first visit each

participant had a DEXA scan to determine bodyfat % and lean body mass. They were also given instructions for tracking their specific start date, end date and details of menstruation and their ovulation for one month. No strength assessments were performed during this first month (the tracking month). The EUM group tracked the start and duration of their menstrual cycle and the timing of ovulation with daily oral temperature readings and luteinizing hormone (LH) strips (Proven™) that were provided (Guida et al., 1999). Each participant was provided instructions on the use of the LH strips in the days surrounding ovulation and how to properly obtain their basal body temperature each morning immediately upon waking. According to manufacturer's instructions, the strips were dipped in urine for 5 s and laid flat for up to 10 minutes to read the ovulation results. Using both daily temperature readings and the LH strip data (Guida et al., 1999), the Ovia fertility tracking app (Ovia Health) was employed to determine the timing of the beginning and end of the follicular and luteal phases.

After the tracking month, four identical experimental sessions were carried out in the second and third months. During this eight-week testing period they continued to use the app to track their cycle using body temperature but did not use the LH strips. For the EUM group, one session was performed in the mid follicular and mid luteal phases in each of the two testing months. For the HBC the testing sessions were timed similarly in the absence of information about menstrual phase. Each HBC participant has a time point indicated with their birth control regimen when their period should be. Based on that timing, testing was scheduled on a cycle like the EUM group with testing approximately (2-3-day window) every two weeks.

3.3 Procedures

3.3.1 Knee Extension Device

A custom testing chair was used for measurement of strength and rate of force development (RFD). Subjects were seated in an upright position with the hip at a 90 degree angle. The pelvis and thighs were firmly secured with straps to prevent movement of adjacent body segments and maintain joint position. Knee extension force was measured perpendicular to the shank with a load cell positioned above the ankle. Force measurements were digitized at 250 Hz (1401 A/D device, Cambridge Electronic Design, UK) and stored on computer using Spike2 software (Spike 2, version 7.14., Cambridge Electronic Design, UK.)

3.2.2 Isometric strength and rate of force development

Rate of force development (RFD) and maximal voluntary contraction (MVC) force was measured from force data recorded from each leg separately during explosive bilateral maximal knee extension tasks. For a trial, participants were instructed to increase the knee extension force as rapidly as possible in both legs simultaneously and then exert a maximal voluntary force for 2-3 seconds (Aagaard, Simonsen, Andersen, Magnusson, & Dyhre-Poulsen, 2002). Strong verbal encouragement was provided for the ballistic start of the trial and during the maximal force portion. The maximal forces were recorded for both legs from each trial during the one min between-trial rest periods. At least three trials were performed with a goal of two maximal force values within 5% of each other for each leg. Additional trials were performed up to a maximum of five trials. The 5% criteria was met for all subjects within five trials (Aagaard et al., 2002).

3.2.3 Vertical jump assessment

The purpose of this test was to measure functional lower limb explosive performance by measuring vertical jump height (Vertec Vertical Jump Trainer, Sport Imports). To set the baseline height of the device, the subject stood upright and reached vertically as far as possible

with the arms together and the fingers extended (Rodriguez-Rosell, Mora-Custodio, Franco-Marquez, Yanez-Garcia, & Gonzalez-Badillo, 2017). The vertical distance from the floor to the tips of the fingers represented the baseline position of the device. Stance width was measured from the preferred jump stance and replicated within-subject for consistency across subsequent tests (Rodriguez-Rosell et al., 2017). An iPod Touch (5th generation) was firmly attached the lateral aspect of the left thigh with Velcro straps to measure the rotation rate of the thigh during the upward propulsion phase of each jump. The face of the iPod Touch was oriented in the sagittal plane.

No pre-propulsion counter movement was allowed. The 90-degree starting knee angle was measured initially with a manual goniometer and then replicated thereafter using an adjustable horizontal rod suspended between two supports. The foot position on the floor was always a known and consistent distance from the rod. Immediately prior to each jump the subject re-assumed the foot stance width and slowly squatted so that the proximal posterior thigh touched the rod. This positioning and procedure ensured that a consistent starting knee angle was established. No swinging of the arms was allowed (Rodriguez-Rosell et al., 2017). While keeping the hands together out stretched above their head, the participants were instructed to jump vertically, complete the upward phase with their arms outstretched straight up, and attempt to touch and move the highest possible indicator on the device. With instruction, three practice jumps were performed at a participant-estimated 25%, 50%, and 75% of maximum (Rodriguez-Rosell et al., 2017). Then, three maximal effort jumps were performed where the subject attempted to move the highest slider possible on the device. At least 30s of rest was provided between each maximal attempt. Care was used to replicate positioning and technique across all jump attempts and testing time points (Rodriguez-Rosell et al., 2017).

3.2.4 *Peak rotation*

In addition to the vertical jump height, the rotation rate of the thigh segment was measured using the gyroscope signal from the iPod Touch. The gyroscope measures the tilt of the device in the pitch axis which provides information about the transverse axis rotation (sagittal plane movement) of the thigh during the upward propulsion phase of each jump attempt. A data collection application (Sensor Data, Wavefront Labs) was used to sample the gyroscope sensor data at 100 samples/s. The application also calculated the rate of rotation around the pitch axis. The data were downloaded to computer and imported into the Spike 2 program for analysis (Cambridge Electronic Design, UK.).

3.2.5 *1-RM Leg press*

The purpose of this task was to determine the maximum inertial load the subjects could lift with a bilateral hip and knee extension. A recumbent leg press machine (Magnum Fitness Systems) was used. The feet were placed in a consistently replicated location on a fixed platform. The leg press action moved the seat backward along polished rails with low-friction bearings. The seat was adjusted, and the feet placed such that the goniometer-measured starting knee angle for the press movement was 100 degrees. Each attempt involved relatively slow (non-ballistic) simultaneous knee and hip extension until the legs were straight. Identification of the 1-RM load involved single lift attempts that began at a moderate load estimated to be approximately 50% of maximum and increased progressively up to maximum, with at least one-minute rest between trials. Subjects were blinded as to not see what weight they were doing or be able to compare it to the next time. They were provided strong and consistent verbal

encouragement during each attempt. When a load was attempted that could not be lifted through the specified ROM, the last successfully lifted load was recorded as the 1-RM load. Intermediate 1kg weights were used to apply more precise loads between each weight plate if necessary. Subjects required 5-8 trials to determine the 1-RM load. Subjects were not allowed to grip the handrails during the testing.

3.2.6 Elbow flexion device

The purpose of this task was to assess maximal voluntary force production for the elbow flexor muscles (Tracy, Dinunno, Jorgensen, & Welsh, 2008). A custom testing chair with a rigid platform for elbow flexion force measurement was used for measurement of maximal voluntary isometric force and rate of force development (RFD). Subjects were seated in an upright position with the torso and left shoulder strapped firmly to the chair. The shoulder was slightly abducted and the elbow at a 100-degree angle. The semi-prone forearm was placed in a form-fitting adjustable plastic orthosis that was fixed to the load cell with the axis of measurement perpendicular to the forearm/orthosis at the position of the wrist. Force measurements were digitized at 250 Hz (1401 A/D device, Cambridge Electronic Design, UK) and stored on computer using Spike2 software (Spike 2, version 7.14., Cambridge Electronic Design, UK.) (Tracy et al., 2008).

3.2.7 Isometric strength and rate of force development

The MVC and RFD measures were obtained using the same procedures and analysis as with the knee extensors. The elbow flexion task was only performed on the left arm due to limitations of the apparatus. This was the non-dominant arm in 21/23 of the subjects.

3.2.7 *Data analysis and reduction*

The MVC tasks were performed bilaterally and values were recorded from each leg separately. The MVC force and RFD values were measured on each leg from the trial with the greatest maximal force value. The length of the lever arm was measured along the lower leg from the center of rotation of the knee joint to the point of application of force into the load cell so the knee extension torque could be expressed. The RFD was quantified as the amount of force (% of maximum torque) generated during specified time periods; 30, 50, 100, and 200 milliseconds. The MVC force was simply the maximal force value from the maximal trial in that session. The MVC values from the left and right legs were summed to produce an overall bilateral MVC value as the KE isometric strength dependent outcome.

For the RFD calculation, the onset of the increase in force was determined using the upper bounds of the noise in the force signal in the 2 seconds prior to the visually evident rise in force (14). A horizontal cursor was placed at the upper bound of the noise and the 0-s timepoint was where this cursor intersected the rising force. This manual, upper-bound, conservative method was chosen in order to ensure that the onset was clearly defined after the rise in force began and was not defined too early due to fluctuations in the baseline force before the task began (Aagaard et al., 2002). The RFD values were obtained by placing cursors at 30, 50, 100, and 200ms after the onset of the increase in force. The slope of the torque increase (% maximum torque/s) was measured for the 0-30, 0-50, 0-100, 0-200ms periods (Aagaard et al., 2002).

The MVC and RFD was analyzed similarly for the knee extensor and elbow flexor task. No lever arm values were measured for the elbow flexors; thus, the strength and RFD values were expressed in units of force (N) and percent of maximum force.

The vertical jump (cm) was calculated as the difference between the baseline position of the device and the highest slider that was moved during the maximum jump attempts.

For the iPod Touch-measured movement speed of the thigh, the peak rotation rate (0.1s window) around the pitch axis was measured from the upward propulsion phase of each maximal jump attempt. The maximal peak rotation rate (rad/s) from all attempts was taken as the dependent outcome for this measure.

3.4 Statistical analysis

Analysis of variance with repeated measures (RMANOVA) was used. The between-subject factor was group; eumenorrheic (EUM) or hormonal birth control (HBC). The within-subjects factors were menstrual phase (follicular or luteal) and month (month one, month two).

Differences between menstrual phases (main effect of menstrual phase) and differences between groups for the effect of menstrual phase were examined via the menstrual phase x group interaction. Within-subjects contrasts (a priori) were examined based on the expectations generated by the research questions. SPSS version 24 was used for the analyses (IBM Statistics).

3. RESULTS

4.1 Subject Characteristics

Thirteen women in the eumenorrheic group (28.2 ± 6 years) and 10 women in the hormonal birth control ($26 \text{ years} \pm 4 \text{ years}$) completed testing. The two groups were similar ($P > 0.05$) for age ($27.2 \text{ years} \pm 5 \text{ years}$), height ($165.3 \text{ cm} \pm 8.6 \text{ cm}$), body mass ($66.5 \text{ kg} \pm 12.2 \text{ kg}$), BMI ($24.1 \text{ kg/m}^2 \pm 3 \text{ kg/m}^2$) lean body mass ($46.3 \text{ kg} \pm 6.9 \text{ kg}$), and body fat percentage ($27.6\% \pm 5.1$).

Table 1.

	Group	Mean	Std. Deviation
Age	Eumenorrheic	28.2	6.2
	HBC	26.2	3.9
BMI	Eumenorrheic	23.5	2.7
	HBC	24.7	2.8
Weight (kg)	Eumenorrheic	63.9	8.6
	HBC	69.1	15.8
Height (cm)	Eumenorrheic	164.2	6.3
	HBC	166.4	10.8
LBM (kg)	Eumenorrheic	44.9	4.7

	HBC	48.0	9.0
BF %	Eumenorrhoeic	27.3	4.6
	HBC	27.9	5.5

4.2 Knee extensor isometric strength

Right vs. left leg. The MVC force for the left leg was significantly less than the right mean (831 ± 194 vs. 891 ± 231 N, $P > 0.05$). There was no group x leg interaction, therefore the right and left leg values were summed to produce a bilateral MVC force value as the main dependent outcome for knee extensor isometric strength. All MVC results for the knee extensors are summed across legs.

Month one vs. month two. Bilateral MVC was reduced by 6% in month two compared with month one (1755 ± 93 vs. 1669 ± 82 N, main effect of month $P = 0.02$). There were no differences in this effect between groups (group x month interaction $P = 0.93$) or between follicular and luteal phases (month x phase interaction $P = 0.47$).

Eumenorrhoeic vs. Hormonal birth control group. Bilateral MVC was not different between groups (1739 ± 117 vs. 1685 ± 128 N, main effect of Group $P = 0.73$). There were no differences in this effect between month one and two (group x month interaction $P = 0.47$).

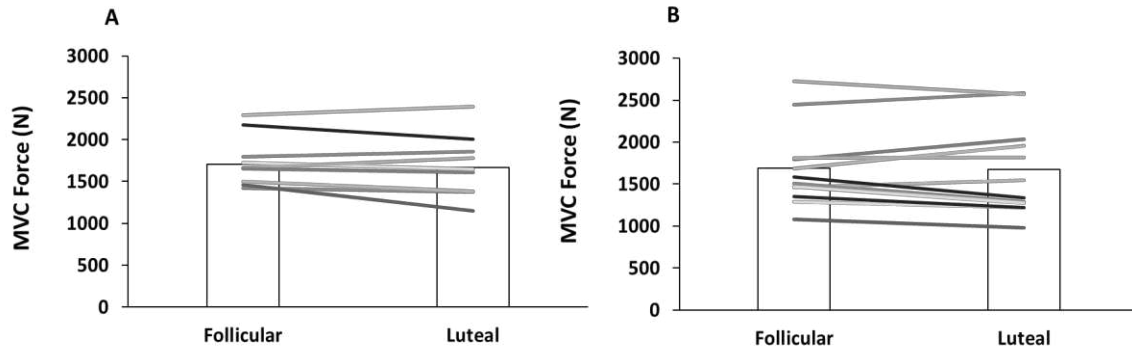


Figure 1. Bilateral knee extensor maximal voluntary contraction force in the follicular and luteal phases for the eumenorrheic (**Figure 1A**) and the hormonal birth control group (**Figure 1B**). There were no significant differences ($p > 0.05$) between phases or groups.

Follicular vs. Luteal phases. Bilateral summed KE MVC was found to be similar between follicular and luteal phases (1723 ± 83 vs. 1701 ± 95 N, main effect of month $P = 0.37$). There were no differences in the phase effect between months (phase x month interaction $P = 0.47$). Bilateral summed KE MVC was not different between follicular and luteal phases for either the EUM group (1744 ± 111 vs. 1735 ± 127 N) or the HBC group (1702 ± 121 vs. 1668 ± 140 N, group x phase interaction $P = 0.73$).

4.3 Elbow flexor isometric strength

Month one vs. month two. Elbow flexion was reduced in testing month two compared with month one (228 ± 10 vs. 215 ± 10 N, main effect of Month $P = 0.01$). There was also a difference in this effect between groups such that month two showed higher isometric strength values compared to the first month (group x month interaction $P = .013$) but no difference between follicular and luteal phases (month x phase interaction $P = 0.12$).

Eumenorrhic vs. hormonal birth control group. Elbow flexor MVC was not different between groups (216 ± 13 vs. 227 ± 14 N, main effect of group $P = 0.84$).

Follicular vs. luteal phases. Elbow flexion MVC was not different between the follicular and luteal phases ($229 \text{ N} \pm 10 \text{ N}$ vs. $215 \text{ N} \pm 10 \text{ N}$, main effect of menstrual phase $P = 0.39$). Elbow Flexion MVC was not different between follicular and luteal phases for the eumenorrhic group ($222 \text{ N} \pm 14 \text{ N}$ vs. $210 \text{ N} \pm 13 \text{ N}$), and hormonal birth control group ($235 \text{ N} \pm 15 \text{ N}$ vs. $220 \text{ N} \pm 15 \text{ N}$, main effect of group by phase $P = 0.84$).

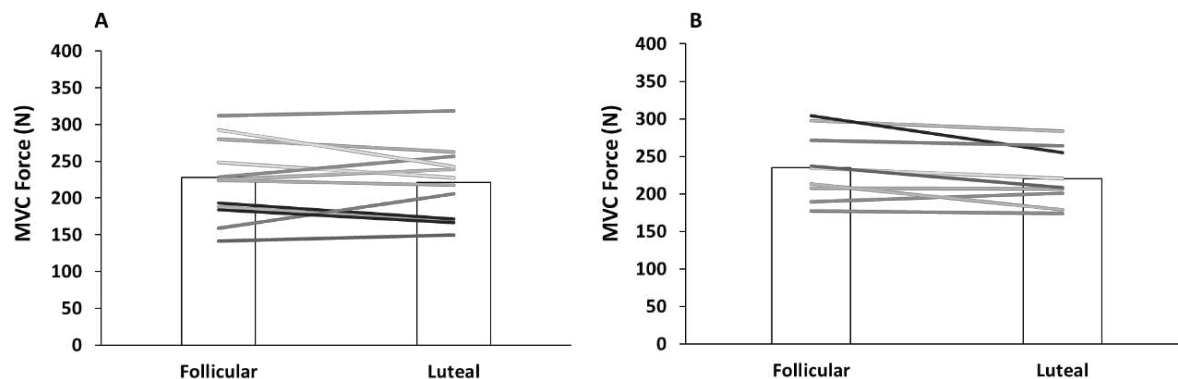


Figure 2. Elbow flexor maximal voluntary contraction force in the follicular and luteal phases for the eumenorrhic (**Figure 2A**) and the hormonal birth control group (**Figure 2B**). There were no significant differences ($p > 0.05$) between phases or groups.

4.4 Leg press dynamic strength

Month one vs. month two. Leg press strength was reduced by 0.8% between month one and month two (130 ± 5 vs. 129 ± 4 Kg, main effect of month $P = 0.01$). There was no difference in this effect between groups (group x month interaction $P = 0.89$) or between follicular and luteal phases (month x phase interaction $P = 0.83$).

Eumenorrhic vs. birth control group. Leg press strength was not different between groups (126 ± 6 vs. 132 ± 7 Kg, main effect of group $P = 0.89$).

Follicular vs. luteal phases. Leg press strength was not significantly different between the follicular and luteal phases (130 ± 5 vs. 127 ± 4 Kg, main effect of phase $P = 0.07$). The two groups were not significantly different, the eumenorrhic group (127 ± 6 vs. 124 ± 6 Kg) compared with the hormonal birth control group (135 ± 7 vs. 130 ± 6 Kg), main effect of group \times phase $P = 0.61$).

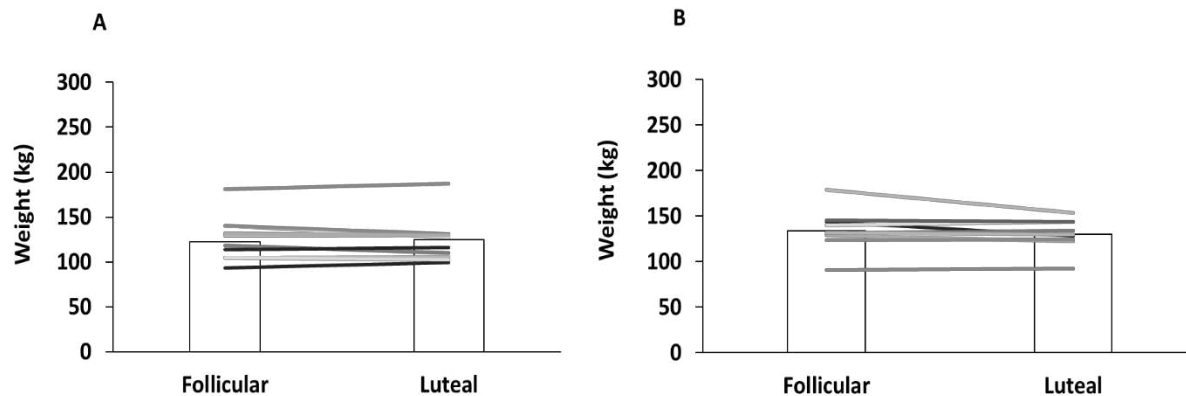


Figure 3. Leg press weight in the follicular and luteal phases for the eumenorrhic (**Figure 3A**) and the hormonal birth control group (**Figure 3B**). There were no significant differences ($p > 0.05$) between phases or groups.

4.5 Vertical jump height

Month one vs. month two. Jump height was the same between month one and month two (31.9 ± 1.3 vs. 31.7 ± 1.2 cm, main effect of month $P = 0.71$). There were no differences in this effect between groups (group \times month interaction $P = 0.23$) or between follicular and luteal phases (month \times phase interaction $P = 0.64$).

Eumenorrhic vs. hormonal birth control group. Jump height was the same between groups (32.7 ± 1.5 vs. 30.9 ± 1.7 cm, main effect of group $P = 0.23$).

Follicular vs. luteal phases. Jump height was not significantly different between the follicular and luteal phases (32.0 ± 1.3 vs. 31.6 ± 1.1 cm, main effect of phase $P = 0.55$). The

difference between phases was not different between the EUM group (32.9 ± 1.7 vs. 32.4 ± 1.5 cm), and HBC group (31.1 ± 2 vs. 30.7 ± 1.7 cm, main effect of group x phase $P = 0.97$).

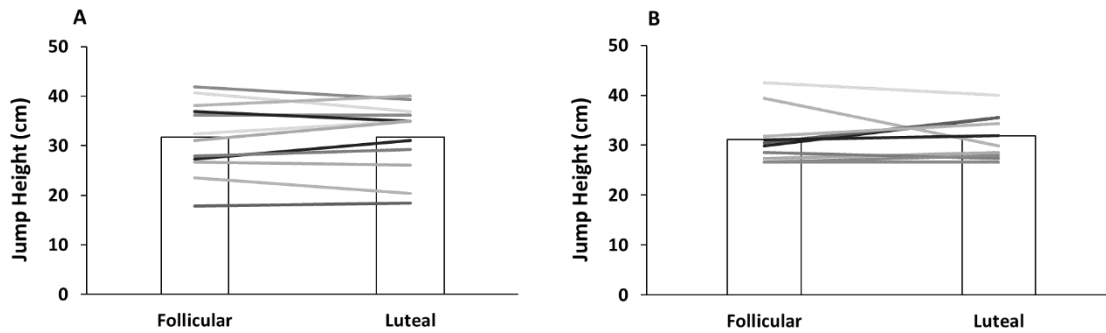


Figure 4. Vertical Jump height in the follicular and luteal phases for the eumenorrheic (**Figure 4A**) and the hormonal birth control group (**Figure 4B**). There were no significant differences ($p > 0.05$) between phases or groups.

4.6 Peak rotation rate

Month one vs. month two. Peak rotation rate was not different between month one and month two (6.97 ± 0.2 vs. 6.94 ± 0.2 rad/s, main effect of month $P = 0.9$). There were no differences in this effect between groups (group x month interaction $P = 0.5$) or between follicular and luteal phases (month x phase interaction $P = 0.4$).

Eumenorrheic vs. hormonal birth control group. Peak rotation rate was the same between groups (6.8 ± 0.298 vs. 7 ± 0.319 rad/s) between follicular and luteal phases (group x phase interaction $P = 0.39$).

Follicular vs. luteal phases. Peak rotation rate was not significantly different between the follicular and luteal phase (6.9 ± 0.20 vs. 7.0 ± 0.26 rad/s, main effect of phase $P = 0.31$). The difference between phases was not different between the eumenorrheic group (6.7 ± 0.27 vs. 6.8

± 0.36 rad/s), and hormonal birth control group (7.0 ± 0.29 vs. 7.3 ± 0.38 rad/s), main effect of group x phase $P = 0.55$).

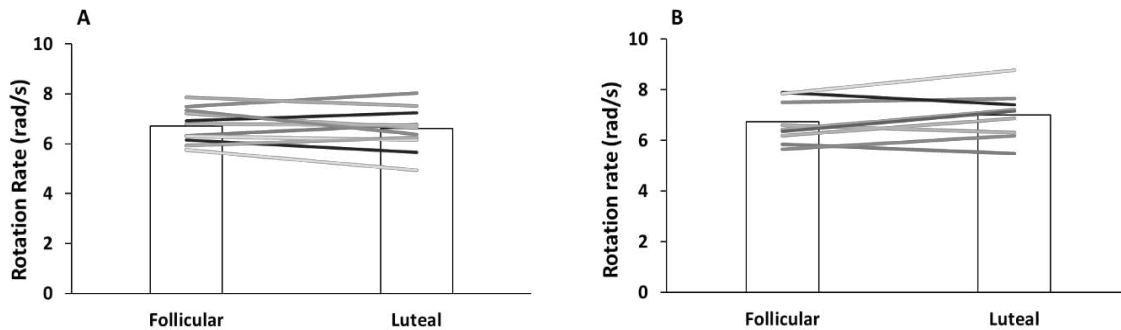


Figure 5. Peak rotation rate in the follicular and luteal phases for the eumenorrheic (Figure 5A) and the hormonal birth control group (Figure 5B). There were no significant differences ($p > 0.05$) between phases or groups.

4.7 Rate of Force Development

4.7.1 Knee Extensors

For the 30, 50, 100, and 200ms time periods, the RFD (%MVC/s) for the elbow flexor muscles was not significantly different between month one and month two, between groups, or between phases (month, group, and phase main effect $P > 0.05$; Figure 6). Furthermore, the EUM and HBC groups exhibited a similar lack of difference between phases (group x phase interaction $P > 0.05$)

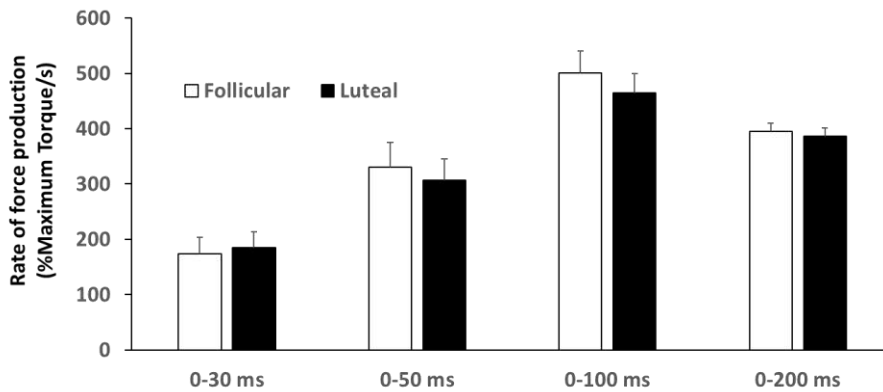


Figure 6. Knee extension rate of force development in the follicular and luteal phases for the eumenorrhic and the hormonal birth control group. There were no significant differences ($p > 0.05$) between phases or groups.

4.7.2 Elbow Flexors

For the 30, 50, 100, and 200ms time periods, the RFD (%MVC/s) for the elbow flexor muscles was not significantly different between month one and month two, between groups, or between phases (month, group, and phase main effect $P > 0.05$; Figure 7). Furthermore, the EUM and HBC groups exhibited a similar lack of difference between phases (group x phase interaction $P >$

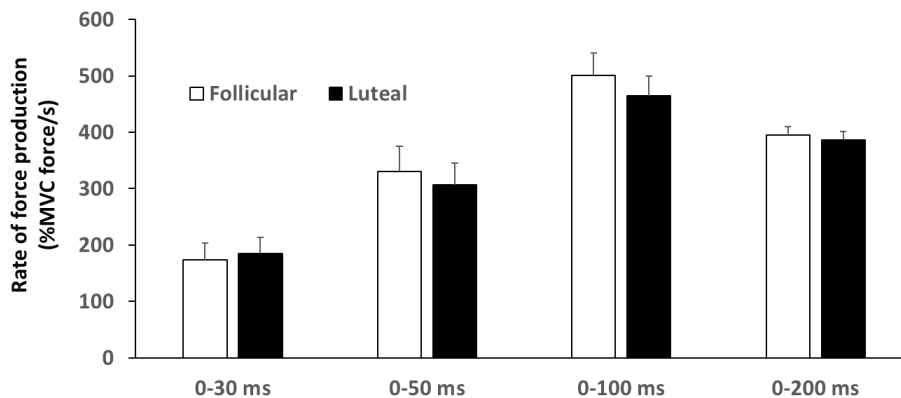


Figure 7. Elbow flexor rate of force development in the follicular and luteal phases for the eumenorrhic and the hormonal birth control group. There were no significant differences ($p > 0.05$) between phases or groups.

0.05).

5. DISCUSSION

The overall objective of the current study was to determine if muscle performance varied between different phases of the menstrual cycle. Outcomes were compared between the follicular and luteal phase and included strength and ballistic force production of the knee extensors and the elbow flexors, vertical jump height, and thigh rotation rate. The strength of both elbow flexors and knee extensors was not different between phases of the menstrual cycle for the eumenorrheic and birth control groups. The vertical jump, an explosive, functional multi-joint muscle performance measurement, also did not vary across the menstrual cycle or between groups. For both leg and arm muscles, the rate of force increases in the earliest phases of contraction (30, 50, 100, 200 ms) was not different between the follicular and luteal phases for either group. Overall, the data suggest no systematic difference in muscle performance between phases of the menstrual cycle.

The most classic study to examine strength during the menstrual cycle reported a significant difference in quadriceps and hand grip strength between the follicular and luteal phases. In the eumenorrheic group both quadriceps and handgrip strength were 11% greater in the follicular compared with luteal phase (Sarwar et al., 1996). They also tested women who were taking hormonal birth control and found that muscle function remained constant across the cycle. They concluded that since women on birth control have a more constant estrogen level, they didn't experience the same changes in muscle function at mid-cycle like the normally cycling women do, who exhibit an increase of estrogen in the follicular phase before ovulation. Similarly, we studied strength output in two consecutive cycles in the mid-late follicular phase (day 8 on average) and the mid luteal phase (day 18 on average) this needs defined sooner.

Sarwar et al determined the menstrual cycle days by counting day one of menses and counting until day 14 assuming that was the ovulation day. We specifically measured ovulation for each participant, determining their ovulation day within 1-2 days. Each participant tracked their cycle with an app, used LH strips, and measured basal body temperature to determine more precisely when they ovulated.

One study also found an increase in strength in the follicular phase. They measured maximum voluntary force (MVF) of the adductor pollicis which was measured over a maximum period of six months (Phillips et al., 1996). Like our study, they tracked ovulation using luteinizing hormone measurements and change in basal body temperature. There was a significant increase in MVF (about 10%) during the follicular phase of the menstrual cycle in both the trained and untrained groups. They also found there to be a drop in MVF shortly after ovulation (Hudgens et al., 1988). Similar, Tenan et al. found that in the in the follicular phase women activate their VMO more than in their luteal phase, also as compared to men, and women on birth control, who saw no differences (Tenan et al., 2013).

De Jonge et al. examined the influence of the different phases of the menstrual cycle on skeletal muscle contractile characteristics and found no differences between phases (Janse de Jonge, 2003). They tested 19 regularly menstruating women. Muscle function was measured when estrogen and progesterone concentrations were low (menstruation), when estrogen was elevated at its peak (ovulation) and when progesterone was low (late follicular phase), and estrogen and progesterone were both elevated (early luteal phase). Maximal isometric quadriceps strength, hand grip strength, fatiguability and electrically stimulated contractile properties were measured along with isokinetic knee flexion and extension strength and fatiguability. They were much more precise with their hormone measurements than our study and determined the

menstrual cycle phases through measurement of estrogen, progesterone, follicle stimulating hormone and luteinizing hormone from blood samples. As with our findings, they found that there were no significant changes in any of the parameters between any of the phases they tested. They did not test women on birth control and do not have an explanation or comparison of the effects that birth control might have on muscle contractility. They concluded that these results suggest the fluctuations in female sex hormones during the menstrual cycle do not influence muscle contractility.

One reason to strive to understand the effects of the menstrual cycle on performance is if, and how, training programs and competition schedules should be structured around the menstrual cycle. Should women plan their training around their cycle to maximize gains in performance? There are several studies that compare training effects between phases. One study compared the effects of strength training in the follicular phase compared with the luteal phase (Sung et al., 2014). One group trained more leg press sessions during the follicular phase and the other group performed more sessions during the luteal phases. They used self-report and a menses-based prediction method to determine ovulation and cycle phases. They found that women who trained more in the follicular phase had a greater increase in strength output after the training period compared with the women who trained more in the luteal phase. Although this study is not directly comparable to our findings, it does at least provide a suggestion that training efficacy could be dependent on the timing of the menstrual cycle.

Other neurological studies have found differences when testing steadiness that were tested via hand gun steadiness during shooting tasks. They found that women in the follicular phase have greater hand steadiness than during the luteal phase and more so than women on birth control in general (Hudgens et al., 1988) . The differences in these studies compared to our

findings is an example of the conflicting nature of the literature in this area. Aside from direct daily blood hormone measurements, there is also not one single method consistently used to determine the exact timing of cycle phases and presumed hormonal fluctuations. If there was one consistent measure used by all researchers to determine cycle timing and hormone levels, there might be more consistent findings.

Most of the parameters tested in studies of the menstrual cycle involve strength and muscle contractility, and performance measures including effects from core temperature changes, aerobic capacity, rating of perceived exertion, and fatiguability. To our knowledge, there have been no measures of the rate of force development in isolated muscle group testing such as we employed. The evaluation of rate of force development during rapid contractions has been employed to characterize the explosive strength of athletes, older adults, and clinical patients (Aagaard et al., 2002), however there is no information that we are aware of on the effect of menstrual cycle phase on rapid force development.

Interestingly, the present results indicate no systematic difference between the phases in strength outcomes or for rate of force development. With this being an important factor regarding athletic performance, knowing that rate of force production doesn't change during the menstrual cycle is new valuable information for all athletes and especially power focused athletes. Physiologically it has been shown, in vivo, that there is an excitatory neurological effect from estrogen (Mazure & Jones, 2015), however, it is possible that effect is not strong enough to produce a change in performance, specifically the rate of force development. The rate of force development is considered to be related primarily to the discharge rate of motor neurons (Aagaard et al., 2002), therefore whatever trophic or potentiating effects that cycle-related

fluctuations in sex hormones might exert on neurons, they were not sufficient to alter maximal voluntary motor output in our study sample.

Many of the other studies in this area had a similar sample size to the present study, mostly ranging between 12-30 (Hudgens, 1988; Sarwar, 1996; Sung, 2014; Mohamed, 2000; Phillips, 1996; Chilibeck et al., 1998) with one study at 100 participants (Pallavi et al., 2017). Pallavi et al found that strength increases in the follicular phase of the menstrual cycle by 10%. They measured strength via hand grip strength across three phases of the menstrual cycle; menses, mid follicular and mid luteal phase early. Seeing that they did find a significant difference it is possible that most studies, including ours, have too few participants to detect differences. This could also explain the inconsistency in findings in this area because too few women are being studied in each study to generate statistical power enough to detect differences should they exist. If a hormonal effect is the underlying phenomenon it might be of small magnitude and therefore difficult to detect with so few participants. Also gathering more data for each participant across several menstrual cycles, as opposed to just one or two cycles, could provide more within-subject data and produce better understanding how these outcomes may fluctuate over time.

Each participant in our study was experienced with strength training at a reasonably high intensity and consistency compared to other studies that have employed a more random sample size including trained and untrained women. If the pervasive anecdotal reports produce a psychological effect, then it could be possible that women who are accustomed to training at a high intensity may psychologically be better able to exert maximal efforts during testing regardless of how they may perceive they are feeling. This could be a possible explanation for not finding any differences between phases.

5.1 Study Limitations

There were a few limitations with our study. First, we did not measure hormone levels throughout the cycle via blood work, which is the gold standard measure to precisely determine hormone levels. We estimated ovulation via LH strips, basal body temperature, and a tracking app. Although reliable, this is still not a definitive method of determining the timing of the hormonal fluctuations for each woman. Time was also a limiting factor with only one person collecting data, so the capacity of the study was dependent on schedules of the administrator and the participant schedules. This limited how many participants could feasibly be tested over the time available. We also did not have precise control over other possible confounding factors such as how much strength training they participated in during the study and when, nutrition, sleep, stress or other factors that can affect performance and hormone levels. They were simply instructed to remain as consistent as possible across the two months of testing, to continue their regimen as normal, and not to train on testing days.

5.2 Future Directions

Future studies should measure more women more extensively over a longer period, so that the strength data is as representative as it can be for an individual. Methods of cycle tracking need to be standardized in order to make optimal comparisons and more precisely pinpoint hormone levels at the time of testing. Less careful tracking in most of the research in this area might have contributed to a lack of consensus in results.

Although an inconsistent finding, more studies are needed to describe the underlying mechanisms that could contribute to putative differences between phases. Further studies could

examine and compare strength trained women and untrained sedentary or recreationally active women. Also, psychological queries at the time of testing could assess the subjective feeling of vigor or performance during testing. The expression of muscle strength begins with a command from the brain, thus this could help to quantitatively measure and explain the perception of feeling weaker and stronger throughout the cycle.

If there are not changes or differences between the follicular and luteal phases, then women should be able to train consistently without reservation and plan competitions without concern that their cycle-related changes in hormone levels will affect their performance. Clinically going forward a rigorous system of understanding and tracking the menstrual cycle in research studies needs to be established and implemented so that women are better represented and included in more research equally to men. However, if there really are no differences, then the need for concern about cycle effects is eliminated and women can be more easily included in studies without concern that there might be differences if they test at different time points in their cycle.

4. CONCLUSION

Overall, we found that there were no differences in maximal force or explosive muscle output between the mid follicular and mid luteal phases of the menstrual cycle. There appears to be no differences between the follicular and the luteal phases or differences between physically active women who are normally menstruating versus those who are taking hormonal birth control. In vivo hormonal variation is suggested to affect muscle function, but this effect is perhaps not strong enough to produce a measurable acute change in muscle performance during the menstrual cycle despite the hormonal variation. It is possible that the anecdotal reports are explained by psychological effects and fluctuations in the perception of effort rather than the underlying neuromuscular physiology. It is possible that there may be a detectable effect with more participants in a larger study or arguably that the difference would be more likely to be seen with frequent measurements across the cycle rather than with a bigger sample size. The results of this study contrast with anecdotal reports of feeling stronger or weaker during different points of the menstrual cycle and implies that women may not need to change training or competition schedules to match their monthly hormonal fluctuations.

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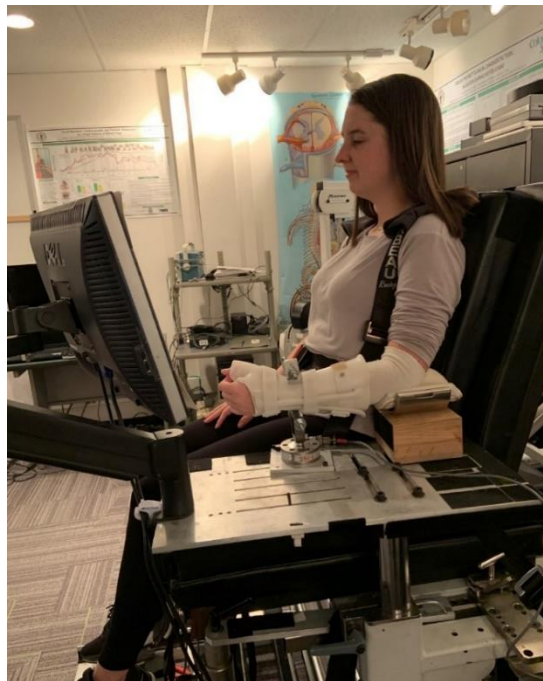
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APPENDIX



Bilateral knee extension maximal voluntary contraction and rate of force development experimental apparatus.



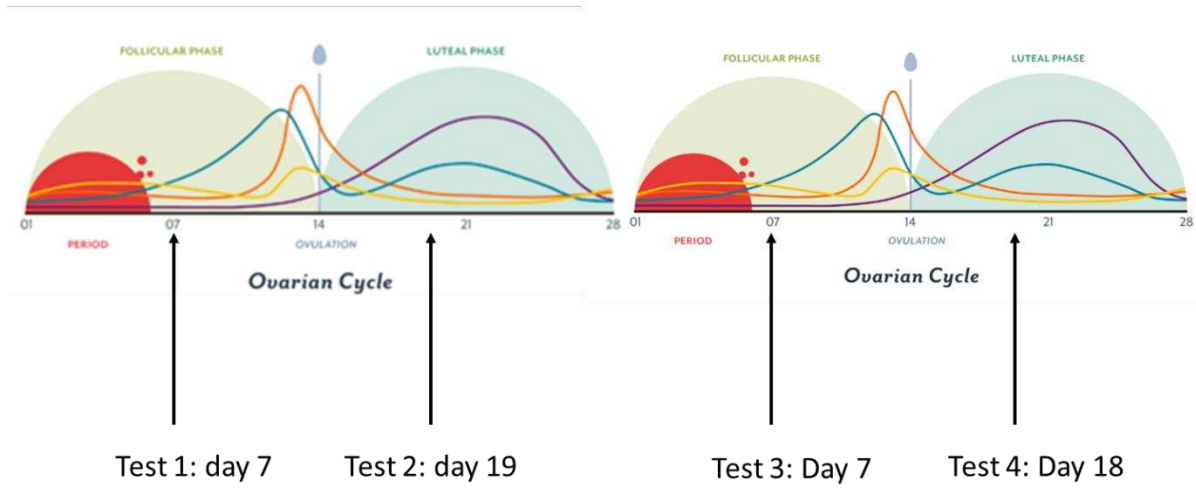
Bilateral knee extension maximal voluntary contraction and rate of force development experimental apparatus.



Vertical jump and peak rotation rate apparatus



Leg press apparatus



Participant testing timeline 