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MATURITY ALTERS DROP VERTICAL JUMP LANDING FORCE-TIME PROFILES BUT NOT PERFORMANCE OUTCOMES IN ADOLESCENT FEMALES.

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ABSTRACT

The stretch-shortening cycle (SSC) assists in effective force attenuation upon landing and augments force generation at take-off during a drop vertical jump (DVJ). General performance outcomes such as jump height or peak measures have been used to assess SSC function in youth populations; however, these discrete metrics fail to provide insight into temporal jump-landing characteristics. This study assessed DVJ force-time profiles in 1013 middle and high-school female athletes (n = 279 prepubertal, n = 401 pubertal, n = 333 postpubertal). Maturity status was determined using the Pubertal Maturation Observation Scale. Ground reaction force data were analysed to extract a range of variables to characterize force-time profiles. SSC function was categorized as poor, moderate or good dependent on the presence of an impact peak and spring-like behaviour. No differences in jump height or ground contact time were observed between maturity groups ($p > 0.05$). Significant differences in absolute peak landing and take-off force were evident between all maturational statuses ($p < 0.05$). Relative to bodyweight normalized forces, only peak take-off force was significantly different between prepubertal and postpubertal groups ($p < 0.05$; $d = 0.22$). Spring-like behaviour showed small improvements from pubertal to postpubertal ($p < 0.05$; $d = 0.25$). Most females displayed poor SSC function at prepubertal (79.6%), pubertal (77.3%) and postpubertal (65.5%) stages of maturity. Large increases in absolute forces occur throughout maturation in female athletes, however, only small maturational differences were found in relative force or spring-like behaviour. Consequently, most girls display poor SSC function irrespective of maturity.

Keywords: plyometric; anterior cruciate ligament; depth jump; growth; maturation

INTRODUCTION

Rebound and plyometric activities that involve the stretch-shortening cycle (SSC) are common-place in sports [1]. These movement patterns are also associated with the aetiology of severe non-contact lower-extremity knee injuries, such as anterior cruciate ligament (ACL) rupture; injuries that have significantly greater incidence rates in adolescent female athletes in comparison to their male counterparts [2]. The drop vertical jump (DVJ) is a commonly utilised screening assessment that is employed both to determine an athlete's competence at rebound activities and to identify aberrant movement patterns that may reflect a heightened risk of severe knee injury [3].

Existing evidence indicates that individuals who go on to sustain an ACL injury have significantly greater peak vertical ground reaction forces during a DVJ than those who remain uninjured [4, 5]. A high peak vertical ground reaction force has also been demonstrated to be a contributing factor to a high-risk profile for ACL injury [6]. Conversely, conflicting research has failed to observe a difference in peak vertical force between injured and uninjured participants [7]. This may relate to the performance demands of the task as the timing of large forces may occur around the midpoint of ground contact. This desirable performance would result in greater vertical impulse that subsequently increases take-off velocity and jump height and could therefore be indicative of a well-trained athlete [8]. Conversely, large ground reaction forces may present a risk factor for injury if they occur in the early period of ground contact if the neuromuscular system is not conditioned to tolerate and absorb such loading [5, 9].

ACL injury rates in females appear to peak around the end of puberty, which indicates that there is an interaction between maturation and injury risk [10]. This apparent rise in injury rates is likely the result of numerous physiological changes including hormonal fluctuations due to menstruation [11] and sub-optimal muscle activation strategies [12] in the presence of increased BMI and lower levels of strength relative to males [13, 14]. The DVJ is a functional test that has been used to observe the impact of these physiological changes on likelihood of ACL injury across maturation. Cross-sectional studies that investigated the effects of maturity status upon DVJ ground reaction forces have typically subdivided the ground contact period into landing and take-off phases and reported peak forces in each of these phases [15, 16]. Given that ACL rupture occur shortly after initial ground contact, peak landing force is of more interest from an injury perspective [9].

Interpretation of relationships between force-time profiles and performance and injury risk will always involve a large degree of speculation when these conclusions are based upon a reductionist approach to analysis of single peak values during ground contact. Recent research in male youth soccer players demonstrates the value of a more granular analysis of the entire force-time profile to gain a better understanding of SSC function [17]. This study showed that mature males, post-peak height velocity, demonstrated better SSC function than pre-peak height velocity individuals when categorised using a combination of the presence or absence of an impact peak and spring-like behaviour [17]. Spring-like behaviour describes the relationship between ground reaction force and centre of mass displacement during ground contact, with a high correlation between the two ($r > 0.80$) required to identify that an individual can rebound in a biomechanically spring-like manner. A correlation between centre of mass displacement and vertical force has previously been applied to female athletes to determine the magnitude of spring-like behaviour for the purposes of calculation of vertical stiffness in a submaximal hopping task [18]. When an athlete displays spring-like behaviour, this could be indicative of increased dampening mechanisms that effectively reduces spikes in ground reaction force during the early part of ground contact through greater preactivation and engagement of the stretch-reflex [19, 20]. This spring-like behaviour was shown to be sensitive to maturation in males [17], but has not been assessed at different stages of maturity in female athletes.

While previous studies have divided the ground contact phase of a DVJ into landing and take-off phases by the time at which peak vertical displacement of the centre of mass occurs, the influence of maturity on the duration of these two phases, or the magnitude of vertical displacement remains unknown. Stiff landings, characterised by reduced hip and knee flexion and centre of mass range of motion, are associated with an increased risk of ACL injury [4]. This elevation in risk is potentially due to yielding of the muscle-tendon unit and the deployment of a strategy that utilises passive tissues (ligament and bone) to decelerate the centre of mass when force requirements exceed the athletes capacity [21]. Given the interaction between maturity and ACL injury incidence in females [10], centre of mass displacement and phase duration analysis are worthy of attention.

A better understanding of the DVJ force-time profiles at different stages of maturity should help identify appropriate training interventions and direct coaching strategies to further improve the effectiveness of training interventions for mitigation of injury risk and enhancement of performance in adolescent females. The purpose of this study was to assess DVJ force-time profiles in a large sample of pre-pubertal, pubertal and post-pubertal female athletes. The hypothesis tested was that while absolute ground reaction forces would be greater in more mature females, SSC function and relative force production would not proportionally adapt beyond puberty.

MATERIALS ANDS METHODS

Participants

The sample was selected from a database of participants previously enrolled in two large prospective, longitudinal studies and comprised 1013 female middle and high school basketball, soccer and volleyball athletes who participated in regular specialized sports training and conditioning for their sport. Sample size was estimated *apriori* using statistical software (G*Power, v3.1.9.2) and considering an effect size of 0.20, alpha level of 0.05, and statistical power of 0.95, a sample size of 390 was required [22]. Participants were required to have no history of anterior cruciate ligament injury or knee surgery and to have been free from lower-extremity injury that required medical intervention for at least 12-months prior to the study. The study protocol was approved by the Institutional Review Board and participant assent and parental consent were collected prior to commencement of the study.

Procedures

Maturity assessment

Maturity status was determined using the Pubertal Maturation Observation Scale (PMOS), comprising a series of questions completed by the parents of the participants, regarding the development of secondary sex characteristics such as menarcheal status, body hair, sweating, muscular definition and a rapid growth in stature [23]. Participants with ≤1 were considered 'prepubertal', those scoring 2-4 were classified as 'pubertal', while participants with ≥5 positive answers were categorized as 'postpubertal'. The PMOS has previously been shown to reliably categorise pubertal status of adolescent females [24].

Drop jump protocol

The DVJ protocol was performed in line with previously published guidelines [25]. Specifically, participants positioned themselves standing on top of a 31 cm box facing two force plates embedded into the floor, measuring vertical ground reaction force at 1200 Hz (AMTI, Watertown, Massachusetts). Participants were instructed to "drop off the box and immediately jump as high as you can". Successful trials required both of the participants' feet to leave the box at the same time, for each foot to land on a separate force plate, and then immediately perform a maximal jump. Participants were allowed to utilise an arm swing to facilitate an effective jump. Failing these criteria, the trials were repeated until three successful trials were recorded.

Data Processing

Force-time data were filtered using a low-pass, fourth-order Butterworth filter with a cut-off frequency of 100 Hz. Participants' three trials were individually analysed using a bespoke MatLab ® (V. 9.4.0.8, Natick, Massachusetts, USA) programme and the mean for each variable was used for further analysis. The ground contact period commenced at the point where vertical force exceeded 10 N and ceased when vertical force dropped below 10 N [24]. Centre of mass displacement was determined by the double-integration of acceleration data, while peak centre of mass displacement was used to separate the landing and take-off phases of the ground contact period. Impact displacement was defined as the percentage of peak displacement that was completed in the first 20% of ground contact time.

Jump height was calculated using flight time [26], while reactive strength index was determined as the ratio of jump height to ground contact time [27]. The highest forces transient in the landing and take-off phases were defined as peak landing force and peak take-off force respectively, and the ratio of peak landing force: peak take-off force was subsequently calculated [15].

Peak force values were allometrically scaled to bodyweight to account for the non-linear relationship between muscular strength and body size. Peak force data and bodyweight were log transformed and then submitted to linear regression. The beta component of the regression equation was subsequently used as the allometric scaling exponent. A Pearson product moment correlation coefficient was computed to confirm that the scaling exponent sufficiently controlled for bodyweight [28].

Participants' SSC function was categorised based on presentation of an impact peak in their force-time profile (defined as the highest transient, visible force peak during the landing phase of ground contact occurring in the first 20% of ground contact) [29, 30], and whether they displayed spring-like behaviour (defined as a Pearson product-moment correlation between vertical ground reaction force and vertical centre of mass displacement during the entire contact phase being < -0.80)[18]. Participants were classified as either 'poor' (impact peak and not spring-like), 'moderate' (impact peak but still spring-like *or* no impact peak and not spring-like) or 'good' (no impact peak and spring-like)[17]. Example force-time profiles of good, moderate and poor SSC function are presented in Figure 1.

INSERT FIGURE 1 NEAR HERE

Statistical Analysis

To determine the effect of maturity status upon DVJ ground reaction force variables, a one-way analysis of variance (ANOVA) was conducted with Bonferroni corrections used to control for multiple comparisons. An alpha level of 0.05 was selected *a priori* to indicate statistical significance. Cohen's d effect sizes were calculated using a pooled standard deviation to determine the magnitude of between-group differences [31]. Effect sizes below 0.2 were categorised as trivial, 0.20-0.59 as small, 0.60-0.1.19 as moderate, 1.20-1.99 as large, 2.00-3.99 as very large and greater than 4.00 as extremely large [32].

Chi-squared (χ^2) analysis was used to investigate the interaction between maturity status and SSC function category. In the Chi-squared test, analysis of the adjusted standardized residuals was completed to identify frequencies that were > 1.96 z-scores ($p < 0.05$) different to the whole group distribution. Adjusted residuals were converted into Chi-squared values and subsequently into p values. The Bonferroni correction was used to produce an adjusted alpha level of $p < 0.006$ in order to reduce the potential for a type I error as a result of multiple comparisons [33].

RESULTS

Table 1 presents anthropometric data for the study cohort. Age (F (2,1013) = 510.617, $p <$ 0.001), body mass (F (2,1013) = 330.691, $p < 0.001$) and height (F (2,1013) = 358.908, $p <$ 0.001) were all significantly different between maturity groups and so all force variables were reported relative to allometrically scaled bodyweight. Linear regression of log transformed force peak and bodyweight data computed an allometric scaling component of 0.89. This adequately controlled for the relationship between body size and relative force (r = 0.004; $p > 0.05$).

INSERT TABLE 1 NEAR HERE

There were no significant differences between any of the maturity groups for jump height (*F* (2,1013) = 2.592, *p* = 0.075), ground contact time (*F* (2,1013) = 0.39, *p* = 0.677) or reactive strength index (*F* (2,1013) = 2.726, *p* = 0.066) with the magnitude of the effect of maturity status upon these variables ranging from trivial to small (*d* = 0.06 – 0.18). From the entire sample, only five subjects achieved a ground contact time < 250 ms (prepubertal *n* = 2; pubertal *n* = 2; postpubertal *n* = 1).

There was no significant effect of maturity status on relative peak landing force (*F* (2,1013) = 1.952, *p* = 0.142) with all between-group effect sizes trivial in magnitude (Table 2). In contrast, there were significant small to moderate (*d* = 0.39-1.11) increases in absolute peak landing force (*F* (2,1013) = 88.042, *p* < 0.001) and significant moderate to large (*d* = 0.84-1.73) increases in peak take-off force (*F* (2,1013) = 227.133, *p* < 0.001) with advancing maturity status. Figure 2 displays example absolute force-time and displacement-time profiles for the median participant for absolute peak landing force in each maturity group. There were also significant between-group differences for relative peak take-off force (*F* (2,1013) = 3.850, *p* < 0.05) with a significant small effect for postpubertal to have greater take-off force than prepubertal. The ratio of relative peak landing force to peak take-off force was significantly influenced by maturity status (*F* (2,1013) = 20.269, *p* < 0.001). Significant small and moderate effects were observed between pubertal and postpubertal, and prepubertal and postpubertal groups respectively, with more mature participants recording lower ratio values. However, there were no significant differences for relative landing to take-off force ratio between prepubertal and pubertal groups. Similarly, peak landing force occurred earlier in pubertal versus postpubertal participants, and earlier in prepubertal versus postpubertal cohorts (*F* (2,1013) = 23.016, *p* < 0.001) with effect sizes small in magnitude. The timing of peak take-off force did not differ between maturity groups (*F* (2,1013) = 0.382, *p* = 0.682). The time interval between peak landing force and peak take-off force was significantly shorter in postpubertal versus pubertal and prepubertal groups (*F* (2,1013) = 5.897, *p* < 0.05), with all effect sizes small in magnitude. However, there was no significant difference between prepubertal and pubertal groups.

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There was a significant between-group effect for centre of mass displacement throughout ground contact (*F* (2,1013) = 19.542, $p < 0.001$); with the less mature subgroups both displayed smaller reductions in displacement in contrast to the postpubertal group. However, there was no significant difference observed between prepubertal and pubertal cohorts. Similarly, impact displacement was significantly different across maturity groups with a small effect for prepubertal and pubertal participants who completed a larger percentage of their maximum displacement in the first 20% of ground contact time than the postpubertal participants (*F* (2,1013) = 23.029, $p < 0.001$). There was a small effect for postpubertal participants to be significantly more spring-like than pubertal or prepubertal (*F* (2,1013) = 9.577, $p < 0.001$), with only 20.4% of prepubertal, 21.9% of pubertal and 31.5% of postpubertal participants classified as spring-like ($r < -0.80$). The postpubertal participants spent a significantly shorter proportion of the ground contact period in the take-off phase of the jump than either the pubertal or prepubertal groups (*F* (2,1013) = 14.784, $p < 0.001$), with these differences small in magnitude.

Chi-squared analysis revealed a significant interaction between SSC function and maturity status (χ^2 (4) = 28.286, $p < 0.001$). A significantly greater proportion of the postpubertal group were categorized as having either ‘good’ (6.0%) or ‘moderate’ (28.5%) SSC function than the proportion of the whole group (Figure 3). However, there were no significant differences between prepubertal and pubertal participants and the whole group.

INSERT FIGURE 3 NEAR HERE

DISCUSSION

The aim of the current study was to quantify the differences in ground reaction force profiles in female athletes of varying maturity status. The main finding demonstrated that performance measures (jump height, ground contact time, reactive strength index) were unchanged across stages of maturity in adolescent female athletes; however, there were alterations to the underlying force-time profiles with advancing maturity. The majority of girls across all maturity levels displayed poor SSC function, typically displaying peaks in landing force and a lack of spring-like behaviour. The data indicate that these differences predominantly happened in the transition from pubertal to postpubertal stages of maturity.

In agreement with previous research, the present study found no significant change in jump height in a DVJ between maturity groups in young females [15]. In rebound tasks such as the DVJ, there are two performance objectives; maximising jump height whilst attempting to minimise ground contact time [25]. The present study is the first to report jump height, ground contact time and reactive strength index in a large sample of adolescent female athletes at different stages of maturity. Male athletes usually increase jump height with maturity [15, 16]; however, female athletes appear to experience neither an increase in jump height nor a reduction in ground contact time and subsequently no change in RSI. Intuitively, the absence of adaptive change in performance variables observed in females at different stages of maturity in the present study reflects an absence of ability to produce force quickly. This is likely a result of the differences in relative strength to body mass that diverges between males and females following the pubertal growth spurt [34, 35].

The present findings underline previous observations that performance outcome measures in a DVJ such as jump height, ground contact time and reactive strength index are independent of an athlete's DVJ force-time profile [36, 37]. Despite these unchanged performance measures across all maturity groups, there was a significant effect of maturity status on most ground reaction force variables. In agreement with previous findings in a small sample of 16 females [16], the current study demonstrates no difference in relative peak landing force between females at different stages of maturity. However, more mature groups did display significantly greater absolute peak landing force; while this became progressively later during ground contact in the more mature groups, this was still within the timeframe to be categorized as an 'impact peak'. Large force peaks in the very early period of ground contact are a concern for ACL injury given the timeframe of ACL rupture early during landing [9]. Increases in peak vertical ground reaction force of just 100 N have been associated with an increased probability of ACL injury of 26% [4]. The between maturity group differences observed in the present study were far in excess of this threshold. Since ACL injury rates increase from late puberty [10], this suggests that these maturity induced changes in DVJ force-time profiles might contribute towards an elevated risk of ACL injury.

While relative peak take-off force was significantly greater in the postpubertal group compared to pubertal, this was only a small effect and consequently landing peak force: take-off peak force ratio remained elevated (~1.5) in the postpubertal group despite reductions in comparison to prepubertal and pubertal cohorts. Subsequently, two-thirds (65.5%) of postpubertal females were categorized as having *poor* SSC function in comparison to previous literature showing that only 9.9% of post peak height velocity (PHV) males have *poor* SSC function [17]. Following the pubertal growth spurt, females will have longer levers and an elevated centre of mass coupled with increased absolute vertical ground reaction forces. This combination of factors will increase joint moments, particularly at the knee joint given the knee-dominant nature of the DVJ [38]. *Poor* SSC function may place excessive loads through passive joint restraints and in combination with greater joint torques this may be a contributary factor to the divergence of ACL injury incidence between postpubertal males and females.

The current study is also the first known to report DVJ centre of mass range of motion at different stages of maturity in a large female population. Prospective injury surveillance studies have identified stiff landings, characterised by a shallow amplitude of centre of mass range of motion, as a risk factor for ACL injury in female athletes [4]. While our data indicate that postpubertal females have significantly greater displacement than their less mature counterparts and complete a smaller proportion of this in the first 20% of ground contact time, the magnitude of these effects were only small. This finding indicates that the majority of females present a profile in which they are *too* stiff upon landing and then quickly yield, which would intuitively lead to a prolonged amortization phase and decoupling of the eccentric and concentric muscle actions. This effect appears to be magnified in the pubertal example centre of mass displacement profiles (Figure 2), with the pubertal participant presenting a more rapid initial drop in centre of mass height and then a flattened curve indicative of an extended transition time from the eccentric to concentric phase of the movement. This phenomemenon is likely excacerbated by increased limb lengths and body mass in the absence of significant increases in strength and power during a period of rapid growth.

Prior evidence demonstrates that good SSC function is actually associated with shallower centre of mass ranges of motion and stiffer landings, which creates an apparent conflict between performance and injury objectives [17]. It might be the case that stiff landings are injurious when SSC function is *poor*, as landing forces exceed the muscle-tendon unit's capacity and are then attenuated by passive structures [39]. When SSC function is *good*, landing forces can be attenuated by the muscle-tendon units and elastic energy is stored in connective tissues; manifested as a spring-like force profile [1]. Previous data report that more than 89% of peak height velocity and post-peak height velocity males display spring-like behaviour [17]; however, the current study observed that fewer than 29% of pubertal and postpubertal females demonstrated this quality. There were moderate improvements in spring-like correlation with advancing maturity in the present study, but the mean value for the postpubertal group was still not spring-like. Between-sex differences in the development of SSC function/spring-like behaviour will likely be associated with sex-specific changes that accompany maturation. Girls may find it more difficult to improve SSC function with advancing maturation, due to increases in fat mass and the absence of a pubertal neuromuscular spurt when compared to boys [13, 34]. Future research should seek to better understand sex related differences in SSC development.

It is evident from these findings that coaching interventions are needed to improve spring-like behaviour in female adolescents through acute coaching and long-term training programs. In the acute training phase this could involve verbal cueing to promote better preactivation and co-contraction of agonist and antagonist muscles prior to initial contact [40]. In addition, it might also be necessary for training exercises to be regressed to reduce eccentric loading and landing forces to facilitate better spring-like behaviour. Submaximal bilateral hopping tasks might be a preferable option to drop jumps for athletes with such requirements. Long-term training programs should seek to develop strength and power to facilitate the dynamic force absorption and rapid force production capabilities necessary to execute spring-like landings in time-constrained ground contacts.

It should be acknowledged that the current study did not utilise kinematic data to provide a complete picture of joint specific displacements and torques. However, the current study provides a novel set of ground reaction force variables that have not previously been investigated in this population at different stages of maturity and which can be applied in field-based settings to detect mechanistic changes in SSC function. Finally, the findings of this study are cross-sectional rather than longitudinal and therefore represent differences between athletes at different stages of maturity rather than changes that happen during maturity. Nonetheless, this analysis was conducted on a large sample of females across three stages of maturation and provides the most comprehensive data available regarding the interaction of DVJ ground reaction force-time profiles and maturity.

PERSPECTIVE

In conclusion, DVJ force-time profiles show moderate improvements with advancing maturity status. While SSC appears to improve with maturity, the current findings indicate that SSC function remains poor in postpubertal females while body mass and absolute forces increase, which might contribute to the disparate incidence of ACL injuries in female compared to male adolescents. In light of the large sample size, the present study also provides benchmark data for a range of novel ground reaction force variables for females at different stages of maturity. Cumulatively, these findings can be used to enhance the effectiveness of injury risk reduction training interventions through a more granular kinetic analysis of SSC function. Given their contribution to DVJ force time profiles, the ratio of peak landing force to take-off force and the degree of spring-like behaviour might be of particular importance for both performance development and injury risk reduction.

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REFERENCES

1. Komi PV. Stretch-shortening cycle: a powerful model to study normal and fatigued muscle. *J Biomech*. Oct 2000;33(10):1197-206.
2. Arendt E, Dick R. Knee injury patterns among men and women in collegiate basketball and soccer. NCAA data and review of literature. *Am J Sports Med*. Nov-Dec 1995;23(6):694-701. doi:10.1177/036354659502300611
3. Pedley JS, Lloyd RS, Read PJ, et al. Utility of Kinetic and Kinematic Jumping and Landing Variables as Predictors of Injury Risk: A Systematic Review. *Journal of Science in Sport and Exercise*. 2020;in press
4. Leppanen M, Pasanen K, Kujala UM, et al. Stiff Landings Are Associated With Increased ACL Injury Risk in Young Female Basketball and Floorball Players. *Am J Sports Med*. Feb 2017;45(2):386-393. doi:10.1177/0363546516665810
5. Hewett TE, Myer GD, Ford KR, et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in

female athletes: a prospective study. *Am J Sports Med*. Apr 2005;33(4):492-501. doi:10.1177/0363546504269591

6. Hewett TE, Ford KR, Xu YY, Khoury J, Myer GD. Utilization of ACL Injury Biomechanical and Neuromuscular Risk Profile Analysis to Determine the Effectiveness of Neuromuscular Training. *Am J Sports Med*. Dec 2016;44(12):3146-3151. doi:10.1177/0363546516656373

7. Krosshaug T, Steffen K, Kristianslund E, et al. The Vertical Drop Jump Is a Poor Screening Test for ACL Injuries in Female Elite Soccer and Handball Players: A Prospective Cohort Study of 710 Athletes. *Am J Sports Med*. Apr 2016;44(4):874-883. doi:10.1177/0363546515625048

8. Bobbert MF, Mackay M, Schinkelshoek D, Huijing PA, van Ingen Schenau GJ. Biomechanical analysis of drop and countermovement jumps. *Eur J Appl Physiol Occup Physiol*. 1986;54(6):566-73.

9. Krosshaug T, Nakamae A, Boden BP, et al. Mechanisms of anterior cruciate ligament injury in basketball: video analysis of 39 cases. *Am J Sports Med*. Mar 2007;35(3):359-67. doi:10.1177/0363546506293899

10. Beck NA, Lawrence JTR, Nordin JD, DeFor TA, Tompkins M. ACL Tears in School-Aged Children and Adolescents Over 20 Years. *Pediatrics*. Mar 2017;139(3)doi:10.1542/peds.2016-1877

11. Wojtys EM, Huston LJ, Boynton MD, Spindler KP, Lindenfeld TN. The effect of the menstrual cycle on anterior cruciate ligament injuries in women as determined by hormone levels. *Am J Sports Med*. Mar-Apr 2002;30(2):182-8. doi:10.1177/03635465020300020601

12. Huston LJ, Wojtys EM. Neuromuscular performance characteristics in elite female athletes. *Am J Sports Med*. Jul-Aug 1996;24(4):427-36. doi:10.1177/036354659602400405

13. Bini V, Celi F, Berioli MG, et al. Body mass index in children and adolescents according to age and pubertal stage. *Eur J Clin Nutr*. Mar 2000;54(3):214-8. doi:10.1038/sj.ejcn.1600922

14. Handelsman DJ. Sex differences in athletic performance emerge coinciding with the onset of male puberty. *Clin Endocrinol (Oxf)*. Jul 2017;87(1):68-72. doi:10.1111/cen.13350

15. Hewett TE, Myer GD, Ford KR, Slauterbeck JR. Preparticipation physical examination using a box drop vertical jump test in young athletes: the effects of puberty and sex. *Clin J Sport Med*. Jul 2006;16(4):298-304.

16. Quatman CE, Ford KR, Myer GD, Hewett TE. Maturation leads to gender differences in landing force and vertical jump performance: a longitudinal study. *Am J Sports Med*. May 2006;34(5):806-13. doi:10.1177/0363546505281916

17. Pedley JS, Lloyd RS, Read PJ, Moore IS, Myer GD, Oliver J. A novel method to categorise stretch-shortening cycle performance across maturity in youth soccer players. *Journal of Strength and Conditioning Research*. 2020;in press

18. Padua DA, Carcia CR, Arnold BL, Granata KP. Gender differences in leg stiffness and stiffness recruitment strategy during two-legged hopping. *J Mot Behav*. Mar 2005;37(2):111-25. doi:10.3200/JMBR.37.2.111-126

19. Gollhofer A, Schmidtbleicher D, Dietz V. Regulation of muscle stiffness in human locomotion. *Int J Sports Med*. Feb 1984;5(1):19-22. doi:10.1055/s-2008-1025874

20. Bhattacharyya KB. The stretch reflex and the contributions of C David Marsden. *Ann Indian Acad Neurol*. Jan-Mar 2017;20(1):1-4. doi:10.4103/0972-2327.199906

21. Read PJ, Oliver JL, De Ste Croix MB, Myer GD, Lloyd RS. Neuromuscular Risk Factors for Knee and Ankle Ligament Injuries in Male Youth Soccer Players. *Sports Med*. Aug 2016;46(8):1059-66. doi:10.1007/s40279-016-0479-z

22. Faul F, Erdfelder E, Lang AG, Buchner A. G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav Res Methods*. May 2007;39(2):175-91. doi:10.3758/bf03193146

23. Davies PL, Rose JD. Motor skills of typically developing adolescents: awkwardness or improvement? *Phys Occup Ther Pediatr*. 2000;20(1):19-42.

24. DiCesare CA, Montalvo A, Barber Foss KD, et al. Lower Extremity Biomechanics Are Altered Across Maturation in Sport-Specialized Female Adolescent Athletes. *Front Pediatr*. 2019;7:268. doi:10.3389/fped.2019.00268

25. Pedley JS, Lloyd RS, Read PJ, Moore IS, Oliver JL. Drop jump: a technical model for scientific application. *Strength and Conditioning Journal*. 2017;39(5):36-44.

26. Leard JS, Cirillo MA, Katsnelson E, et al. Validity of two alternative systems for measuring vertical jump height. *J Strength Cond Res*. Nov 2007;21(4):1296-9. doi:10.1519/R-21536.1

27. Flanagan EP, Comyns TM. The use of contact time and the reactive strength index to optimize fast stretch-shortening cycle training. *Strength and Conditioning Journal*. 2008;30(5):32-38.

28. Cleather DJ. Adjusting powerlifting performances for differences in body mass. *J Strength Cond Res*. May 2006;20(2):412-21. doi:10.1519/R-17545.1

29. Hreljac A. Impact and overuse injuries in runners. *Med Sci Sports Exerc*. May 2004;36(5):845-9.

30. Nicol C, Komi PV, Marconnet P. Fatigue effects of marathon running on neuromuscular performance: changes in muscle force and stiffness characteristics. *Scand J Med Sci Sports*. 1991;1:10-17.

31. Cohen J. *Statistical power analysis for the behavioural sciences*. Routledge Academic; 1988.

32. Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc*. Jan 2009;41(1):3-13. doi:10.1249/MSS.0b013e31818cb278

33. Beasley T, Schumacker R. Multiple regression approach to analyzing contingency tables: post hoc and planned comparison procedures. *The Journal of Experimental Education*. 1995;64(1):79-93.

34. Hewett TE, Myer GD, Ford KR. Anterior cruciate ligament injuries in female athletes: Part 1, mechanisms and risk factors. *Am J Sports Med*. Feb 2006;34(2):299-311. doi:10.1177/0363546505284183

35. Hewett TE, Myer GD, Ford KR. Decrease in neuromuscular control about the knee with maturation in female athletes. *J Bone Joint Surg Am*. Aug 2004;86-A(8):1601-8.

36. Snyder BW, Munford SN, Connaboy C, Lamont HS, Davis SE, Moir GL. Assessing Plyometric Ability during Vertical Jumps Performed by Adults and Adolescents. *Sports (Basel)*. Oct 27 2018;6(4)doi:10.3390/sports6040132

37. Healy R, Kenny IC, Harrison AJ. Reactive Strength Index: A Poor Indicator of Reactive Strength? *Int J Sports Physiol Perform*. Jul 1 2018;13(6):802-809. doi:10.1123/ijspp.2017-0511

38. McBride JM, Nimphius S. Biological system energy algorithm reflected in sub-system joint work distribution movement strategies: influence of strength and eccentric loading. *Sci Rep*. Jul 21 2020;10(1):12052. doi:10.1038/s41598-020-68714-8

39. Beynnon BD, Fleming BC. Anterior cruciate ligament strain in-vivo: a review of previous work. *J Biomech*. Jun 1998;31(6):519-25.

40. Croce RV, Russell PJ, Swartz EE, Decoster LC. Knee muscular response strategies differ by developmental level but not gender during jump landing. *Electromyogr Clin Neurophysiol*. Sep 2004;44(6):339-48.

Data Availability

Research data are not shared due to privacy and ethical restrictions.

Table Titles

Table 1. Anthropometric data for each maturity group.

Table 2. Drop vertical jump ground reaction force variables and derivatives for athletic high-school females at different stages of maturation.

Figure Titles

Figure 1. Example force-time profiles of poor, moderate and good stretch-shortening cycle function.

Figure 2. Example force-time and centre of mass displacement-time profiles of the median participant for absolute peak landing force in each maturity group.

Figure 3. Proportions of participants categorised as having poor, moderate or good stretch-shortening cycle function at different stages of maturation. * significantly different to the proportion within the whole group $p < 0.05$

Table 1. Anthropometric data for each maturity group.

	Prepubertal (n = 279)	Pubertal (n = 401)	Postpubertal (n = 333)
Age (yrs)	11.9 ± 0.6$^{*\#}$	12.5 ± 1.1	14.8 ± 1.6*
Body mass (kg)	40.1 ± 8.1$^{*\#}$	51.2 ± 10.4	60.6 ± 10.4*
Height (cm)	149.1 ± 6.4$^{*\#}$	158.2 ± 7.1	164.4 ± 7.5*

[*] significantly different to Pubertal

[#] significantly different to Postpubertal

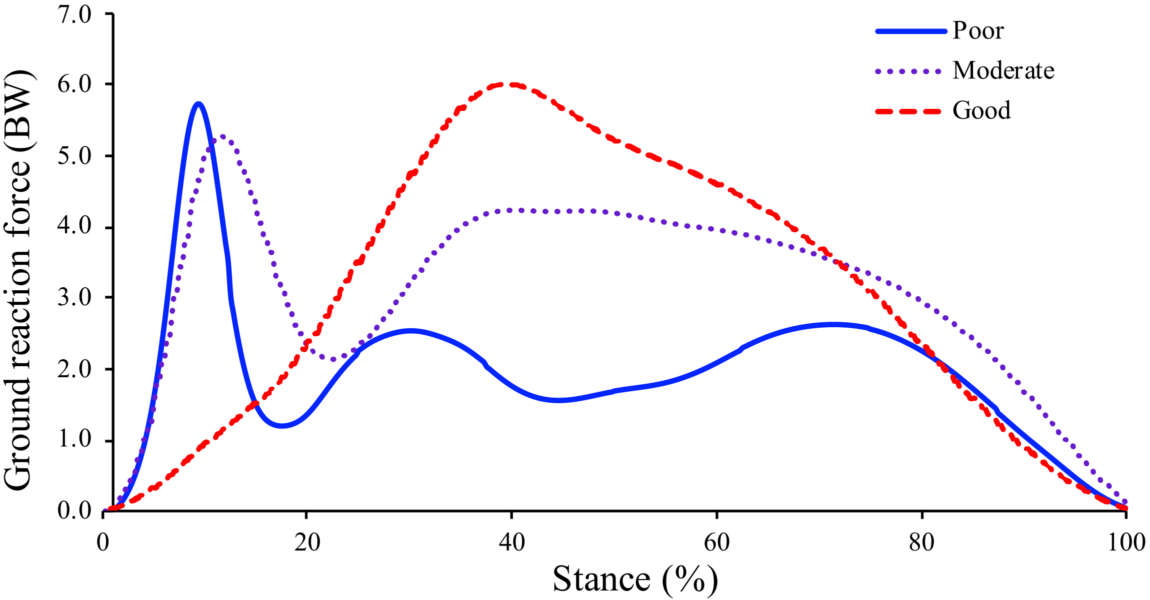
Table 2. Drop vertical jump ground reaction force variables and derivatives for athletic high-school females at different stages of maturation.

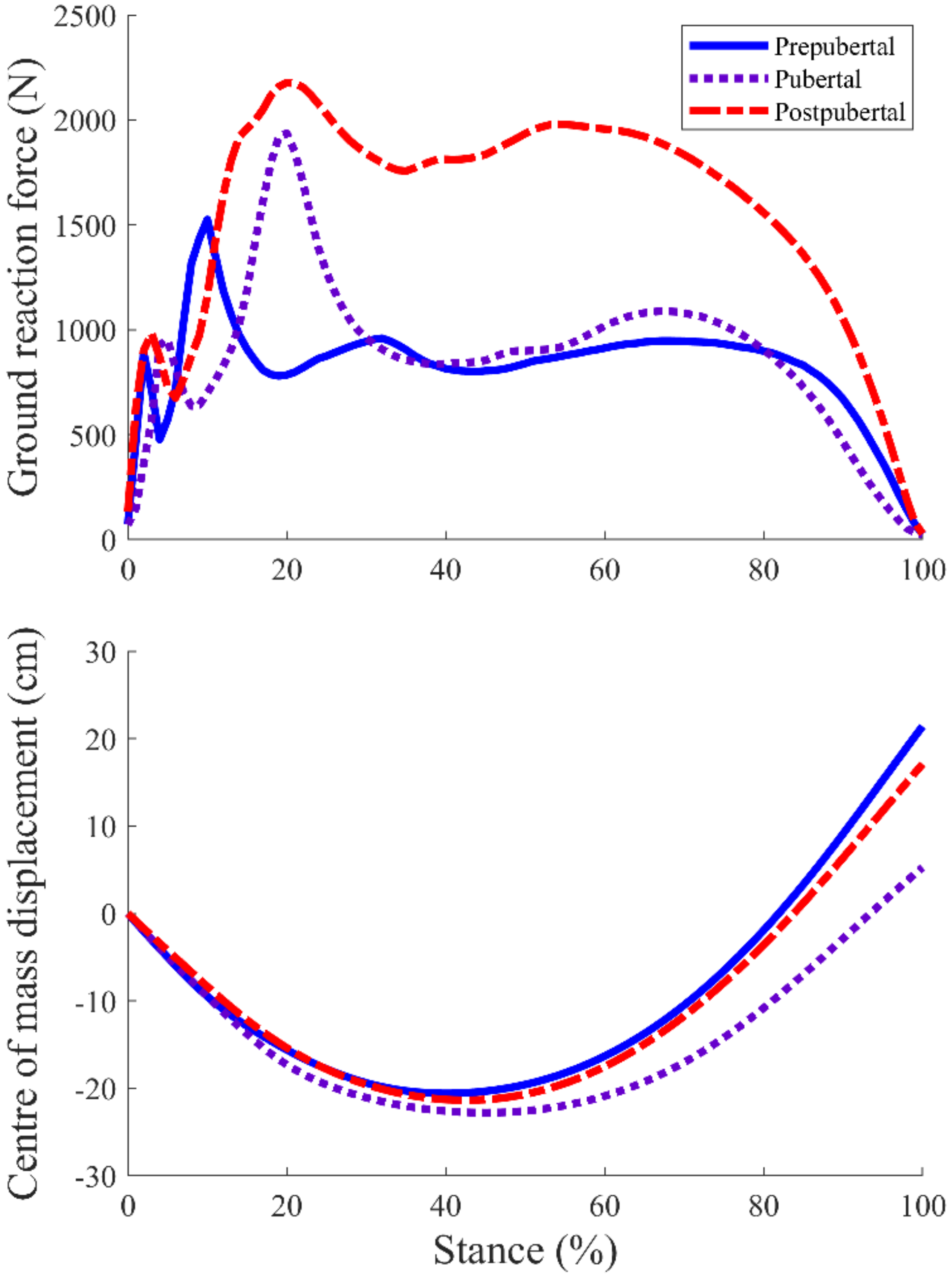
	Mean ± SD			Cohen’s d Effect Size		
	Prepubertal	Pubertal	Postpubertal	Prepubertal vs Pubertal	Pubertal vs Postpubertal	Prepubertal vs Postpubertal
Jump height (cm)	25.81 ± 6.80	24.52 ± 7.18	25.03 ± 7.66	-0.18	0.07	-0.11
Ground contact time (s)	0.421 ± 0.08	0.426 ± 0.08	0.421 ± 0.08	0.06	-0.06	-0.01
Reactive strength index	0.65 ± 0.24	0.61 ± 0.23	0.62 ± 0.24	-0.18	0.08	-0.10
Peak landing force ($BW^{0.89}$)	8.71 ± 1.54	8.49 ± 1.64	8.48 ± 1.66	-0.13	-0.01	-0.14
Peak take-off force ($BW^{0.89}$)	5.19 ± 0.92	5.24 ± 0.91	5.40 ± 1.07^{a}	0.05	0.17	0.22
Landing peak: take-off peak ratio	1.68 ± 0.48	1.66 ± 0.41	1.45 ± 0.64^{ab}	-0.05	-0.54	-0.58
Peak landing force time (%)	13.53 ± 5.32	14.31 ± 5.56	16.49 ± 6.17^{ab}	0.14	0.37	0.49
Peak take-off force time (%)	57.47 ± 11.06	57.56 ± 10.43	56.91 ± 10.49	0.01	-0.06	-0.05
Landing-take-off time difference (%)	43.94 ± 14.33	43.25 ± 13.52	40.41 ± 13.73^{ab}	-0.05	-0.21	-0.25
Centre of mass displacement (cm)	23.71 ± 4.25	24.26 ± 4.33	25.83 ± 4.73^{ab}	0.13	0.34	0.46
Impact displacement (%)	71.25 ± 4.89	71.05 ± 5.03	68.83 ± 5.31^{ab}	-0.04	-0.42	-0.46
Spring-like correlation	-0.61 ± 0.22	-0.63 ± 0.20	-0.68 ± 0.20^{ab}	-0.09	-0.25	-0.33
Take-off phase duration (%)	55.29 ± 4.36	55.13 ± 4.13	53.67 ± 4.25^{ab}	-0.04	-0.35	-0.37

BW- Bodyweight

[a] significantly different to prepubertal; $p < 0.05$

[b] significantly different to pubertal; $p < 0.05$


7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Ground reaction force (BW)
0
20
40
60
80
100
Stance (%)
Poor
Moderate
Good



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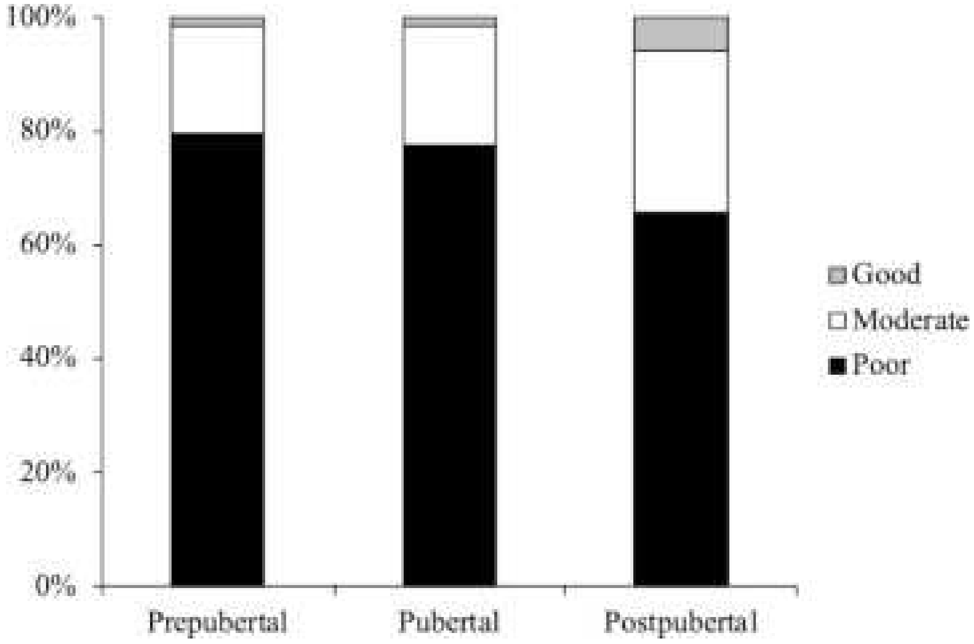

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