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Title Page:

DOES RESISTED SLED TOWING IMPROVE THE PHYSICAL QUALITIES OF ELITE YOUTH SOCCER PLAYERS OF DIFFERING MATURITY STATUS?

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Abstract:
Purpose: Sled towing has been shown to be an effective method to enhance the physical qualities in youth athletes. The aim of this study was to evaluate the impact of a 6-week sled towing intervention on muscular strength, speed and power in elite youth soccer players of differing maturity status.

Method: Seventy-three male elite youth soccer players aged 12–18 years (Pre-Peak Height Velocity [PHV] n=25; Circa-PHV n=24; Post-PHV n=24) participated in this study from one professional soccer academy. Sprint assessments (10 and 30 m), countermovement jump and isometric mid-thigh pull were undertaken before (T1) and after (T2) a 6-week intervention. The training intervention consisted of 6 weeks (2 x per week, 10 sprints over 20 m distance) of resisted sled towing (linear progression 10 to 30% of body mass) during the competitive season. Bayesian regression models analysed differences between T1 and T2 within each maturity group.

Results: There were minimal changes in strength, speed and power (p=0.35-0.80) for each maturity group across the 6-week intervention. Where there were changes with greater certainty, they are unlikely to represent real effect due to higher regression to the mean (RTM).

Conclusion: It appears that a 6-week sled towing training programme with loadings of 10-30% body mass only maintains physical qualities in elite youth soccer players Pre-, Circa-, and Post-PHV. Further research is required to determine the effectiveness of this training method in long-term athletic development programmes.

Keywords: youth development; long-term athletic development; maturation; strength; speed; IMTP

Declarations:
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Code availability: Code for Bayesian modelling can be provided upon request (R Studio, R script software).
Authors' contributions:

INTRODUCTION

Many soccer academies are investing resources into the physical development of their players (Wrigley et al. 2014). However, the large discrepancy of facilities and resources available throughout academy structures may be a limiting factor that hinders the physical development of such players. As such, not all academies have sports science support to facilitate physical development across the entire pathway, which may have a knock-on effect on weightlifting competency as the players get older may hinder development. From a research perspective, many resistance training studies have failed to equate training volume and load across gym-based interventions making it difficult to understand differences in development between maturity groups. However, sled towing may offer a cheap and effective alternative to enhancing strength, speed and power; which are essential physical qualities for soccer (Deprez et al. 2013), while also offering the opportunity to undertake controlled and balanced interventions across maturity groups to understand the influence of maturation on training adaptations. While the primary focus of this study is to offer an alternative for clubs with limited facilities etc, this is not to say, sled towing can't supplement training interventions for those practitioners that have the luxury of gym facilities and staffing.

Sled towing is a popular training method in adult populations (Cross et al. 2017; Lockie et al. 2012; Petrakos et al. 2016) and has been demonstrated to improve acceleration, maximum velocity and its underlying mechanisms (e.g., maximal net horizontal ground reaction force; Morin et al. 2017). Lighter loads are reported to improve maximum velocity capabilities (Harrison and Bourke 2009; Lockie et al. 2003) while heavier loads target acceleration (Kawamori et al. 2014). More recently, the use of heavier loadings that cause a velocity loss of 50% (Cross et al. 2018), is believed to target training conditions that produce maximal power output (optimal force and optimal velocity; Cormie et al. 2011) to enhance performance (Cormie et al. 2007; Kawamori and Haff, 2004; Wilson et al. 1993). However, limited evidence exists using this method in youth populations and the impact it may have on physical development, especially considering maturity status.

Within youth athletes, the evidence base on the use of sled towing is less developed (Cahill et al. 2019a; Cahill et al. 2019b; Rumpf et al. 2015). Recently Cahill et al. (2019c) demonstrated improved physical performance following a sled pushing intervention; however, the authors suggested that many differences exist between sled pushing and pulling which likely result in unique kinematic and kinetic changes and sled pushing should be viewed as a unique and specialised form of horizontal resistance training. With this in mind, only one study to date (Rumpf et al. 2015) has investigated sled towing (pulling) in elite youth athletes across a range of maturity statuses. Rumpf reported a 6-week sled intervention improved the speed, stride length, stride frequency, force, and power in pubertal boys, but it had no benefit for prepubertal boys. These findings suggested sled towing may improve other physical qualities and not just speed. Therefore, sled towing might be a practical method to enhance relative force production across maturity groups. However, Rumpf et al.'s (2015) study had limitations including; 1) the utilisation of a non-motorized treadmill which has been shown to place an inherent resistance, reducing the maximal speed obtained, compared with overground sprinting (Morin and Sève, 2011; Cross et al. 2017); 2) the combination of the Circa- and Post-PHV groups, make it difficult to partition out the maturation effect; and 3) their statistical approach should be interpreted with caution given the growing concerns when using a p-value to make inferential assumptions on group differences (Wasserstein and Lazar 2016) and the reporting of a percentage change pre and post-intervention, rather than the inclusion of baseline performance as a covariate (Senn 2006) which may inflate the findings.

To summarise, maturity status is an important consideration when aiming to optimise youth athlete development. However, practitioners working with youth athletes may experience challenges (i.e., time, facilities, athlete competence) for optimising strength, speed and power development and researchers may fail to implement controlled and balanced training programmes across differing maturity groups. This is apparent given the limited studies investigating across a range of maturity statuses in elite youth soccer players (Moran et al. 2018). Although Rumpf et al. (2015) investigated, a sled towing intervention in elite youth athletes' limitations exist in their study. Therefore, the purpose of this study was to evaluate a 6-week sled towing intervention using relative loadings (10, 20, 30% body mass) on speed, strength and power performance in youth soccer athletes across maturity statuses (Pre-, Circa- and Post-peak height velocity; PHV).

METHODS

Subjects

Seventy-three male elite youth soccer players aged 12–18 years (Pre-PHV n=25; Circa-PHV n=24; Post-PHV n=24) were recruited from one professional soccer academy (Table 1 for descriptive data). The Pre-PHV and Circa-PHV participants trained on average four football sessions per week, with one competitive match and the Post-PHV group trained on average, six football training sessions and one competitive match per week. The sled towing intervention replaced their usual S&C practices. All experimental procedures gained institutional ethics approval with informed and parental written consent obtained.

Experimental Approach to the Problem

A pre (T1) and post (T2) intervention study design was used to assess the impact of a 6-week sled towing intervention on speed, power and strength performance in elite youth soccer players. The study was implemented in-season, and testing took place at week 1 and week 8 with the intervention implemented on weeks 2-7. Before data collection, the players attended a familiarisation session that consisted of 10 x 20m sled towing sprints (FH Pro Mini Speed Sledge Team Series; Dimensions; 53 cm length 38 cm width 22 cm height, 300 grams) with no additional weight attached. All testing and sled sessions were conducted on a 3G surface for consistency and took place at least 48 hours post competitive match-play for all participants (see video 1). Before testing and the training intervention, all subjects performed a standardised 10-minute warm-up consisting of jogging, dynamic stretching and acceleration drills. The players were accustomed to the physical tests as they were a part of their standard testing battery.

Procedures

Anthropometry

Height and sitting height were measured to the nearest 0.1cm using a Seca Alpha stadiometer. Body mass was determined from body weight and taken to be BWg-1 (kg) with g = acceleration due to gravity measured on a commercially available portable force platform (AccuPower, AMTI, ACP, Watertown, MA) using a sampling rate of 1,000 Hz then multiplied by 9.81 to convert to kg.

Maturity offset

Age at PHV was estimated by the Mirwald prediction equation (Mirwald et al. 2002). Years from PHV (YPHV) was calculated for each subject by subtracting the age at PHV from chronological age with a ±6month error rate. Subjects were allocated to either Pre-PHV (offset < -1 years), Circa-PHV (between -0.99 to +0.99 years) or Post-PHV (> +1 years) groups in relation to their YPHV (Morris et al. 2018a).

Sprint Performance

For sprint performance, distances of 10 and 30 m were assessed using Brower photocell timing gates (model number BRO001; Brower, Draper, UT, USA). All subjects performed two trials, with 3-5 minutes of rest between trials. Athletes started 0.5 m behind the first gate from a 2-point staggered start (Thomas et al. 2015). The best performance from each of the 2 trials was used for analysis. Intraclass correlation coefficient (ICC) and coefficient of variation (CV) for 10 m were r=0.84 and CV=3.6% and 30 m were r=0.81 and CV=2.5%.

Isometric Mid-Thigh Pull (IMTP)

The IMTP was utilised as a measure of lower body strength. The IMTP was performed on a commercially available portable force platform (AccuPower, AMTI, ACP, Watertown, MA) and recorded vertical force at 1,000 Hz. The data was not filtered. Subjects performed the IMTP on a customized pull rack with their shoulders placed over the bar in a position similar to 1 that of the second pull of a power clean (Haff et al. 2015). Subjects performed two IMTP trials, each lasting 6 seconds (the pull lasting 5 seconds), with 3 minutes' rest between trials. The IMTP start was identified using a 5 SD threshold that was calculated from 1 second of quiet standing force recorded before the start of each pull (Morris et al. 2018b). Participants were instructed to push as "fast and hard" as possible and received loud verbal encouragement (Morris et al. 2018b). Each participant's best trial, as determined by the highest peak force (PF), was selected for analysis. Relative peak force (rPF) and relative impulse at 100 (rImp100) and 300 ms (rImp300), was calculated as PF/body mass, impulse/body mass. ICC and CV for the IMTP variables were as follows; PF and rPF were r=0.98 and CV=4.91%. For Imp100 and Imp300, ICC and CV were r=0.88, CV=5.0%; r=0.84, CV=8.5%, respectively. Relative Imp100 and rImp300 were r=0.88, CV=9.6%, r=0.84, CV=9.8%, respectively.

Countermovement Jump (CMJ)

The CMJ was utilised as a measurement for lower body power. The CMJ was performed on the same portable force platform sampling vertical force (Fz) at 1,000 Hz, which was not filtered. After a 1 second quiet standing period to identify initiation of movement, using the same 5SD threshold (Chavda et al. 2018) CMJ was performed utilising a standard technique with arms akimbo (Hori et al. 2008), with no attempts made to control the depth of the countermovement (Morris et al. 2018a). Each participant performed 2 jumps interspersed with 3 minutes rest. Jump height was calculated using the velocity at take-off method (Morris et al. 2018a) whilst net force was integrated with respect to time to obtain net impulse, which was summed over the propulsion phase. ICCs and CVs for the CMJ jump height (JH) were r=0.86, and CV=7.5% and CMJ impulse (CMJImp) were r=0.94 and CV=6.7%.

Training Intervention

The training intervention consisted of 6-weeks of resisted sled towing, two sessions per week with a total of 12 sessions during the competitive season. The players had to have completed ten or more sessions (out of a total of 12), which is above an adherence rate of 80% to be included in the T2 post-testing session. From the start of the intervention, there were 102 players, across the age groups, with 73 players completing 10 or more sessions. This is an adherence rate of 72%. Each session consisted of 10 sprints over 20 m distance. The recovery between sets was approximately 90 seconds. Sessional training volume (calculated by number of sprints X distance X load) as reported by Rumpf et al. (2015), which was altered every two weeks (every four sessions) by increasing the relative loads on the sleds from 10% (weeks 1-2; session load 20,000 AU), 20% (weeks 3-4; 40,000 AU) and 30% (weeks 5-6; 60,000AU). No other load was monitored was monitored during this intervention.

Statistical Analysis

Descriptive statistics are reported as mean and standard deviation (SD) and median and median absolute deviation (MAD). To model pairwise differences between pre and post-scores within each maturity group, Bayesian regression models were fitted using a Student-t distribution (Aas and Haff 2006) and allowing unequal variances between conditions. Weakly informative priors were used which included an improper flat prior over the reals for b values, a half Student-t prior with 3 degrees of freedom and a scale parameter of 10 for sigma with gamma on nu (shape=2 and rate=0.1). To illustrate the uncertainty around the estimation, lower and upper 95% Higher Density Intervals (HDI) are reported. Probability values of a change being greater or less than 0 (p>0 or <0) are provided and a standardised effect size calculated from the posterior estimates along with lower and upper 95% HDIs. For purposes of comparison, the effect sizes (ES) 0.2, 0.5 and 0.8 were considered to represent small, moderate and large differences, respectively (Cohen 1992). The percentage of regression to the mean (RTM) was calculated. This was done because RTM can make a natural variation in repeated measures data look like real change. All models were checked for convergence ($\hat{r}$=1), visual posterior predictive checks were conducted no systematic discrepancies between the predictive distribution and observed data y (Gabry et al. 2019). All analyses were conducted using R (Team 2019) and with the Bayesian Regression Models in Stan (brms) package (Bürkner 2017) which uses Stan (Team 2016) for Hamiltonian Markov Chain Monte Carlo (MCMC). ICC's and CV's were analysed for the performance variables described above during T1 and between repetitions.

RESULTS

The mean and SD for anthropometric and maturation characteristics are displayed in Table 1. Table 2-3 present the mean (SD) and median (MAD) descriptive statistics for performance measurements at T1 and T2. Tables 4-6 display the inferential statistics for each maturity group.

Insert Table 1, 2, 3 near here

Pre-PHV

The means for T1 and T2 suggest minimal improvements occurred across all performance variables apart from 10 m sprint performance and CMJ jump height (Table 2; Figure 1, 2, 3). The median suggest all performance measures improved except CMJ impulse and jump height (Table 3). The estimated differences suggest any improvement post-intervention for the Pre-PHV are highly uncertain (Table 4). There was also high RTM across measures, implying that even where differences were associated with less uncertainty, they are unlikely to represent real effect. The standardised differences (ES) across all measures, at best, represent small effects, and again these are highly uncertain. Overall, the results suggest the 6-week sled intervention did not change physical qualities within the Pre-PHV group.

Insert Figures 1,2,3 near here

Circa-PHV

The descriptive statistics (mean and median) suggest minor improvements across most performance variables except CMJImp and rImp300 where performance declined (Table 2-3; Figure 1, 2, 3). Modelled population differences for the Circa-PHV group were highly uncertain in terms of the intervention improving performance (Table 5). The standardised differences (ES) across all measures, represent small effects at best and are again highly uncertain. Overall, the results suggest no change in physical qualities within the Circa-PHV group.

Post-PHV

Data suggest minor improvements across all performance variables apart from CMJImp, JH, rImp100, PF and rPF (Table 2). The median suggests improvements in only 10 m and 30 m sprints, CMJImp, and Imp300, the remaining variables suggested decreases from T1 to T2 (Table 3; Figure 1, 2, 3). As with the other two groups, the estimated differences for the Post-PHV group suggests that most differences are highly uncertain for the intervention being successful in improving performance (Table 6). While there are performance increases for Imp300 and rImp300, appear less uncertain these variables had very high levels of RTM and are unlikely to represent a real effect of the intervention as a result. Again, the ES across all measures demonstrated a small and highly uncertain effects. Overall, the results show high levels of uncertainty and RTM; and no change within Post-PHV players.

Insert Table 4, 5, 6 near here

DISCUSSION

This study aimed to evaluate the effect of a 6-week sled towing intervention on the physical qualities of youth soccer players across Pre-, Circa-, and Post-PHV maturity groups. The current findings suggest that the sled towing intervention had minimal impact on the physical qualities of youth soccer players across all maturity groups. The result showed uncertainty and RTM and therefore observing a real effect was unlikely across all groups. These findings suggest that a bi-weekly sled towing training intervention for 6 weeks may not change the physical performance of youth soccer players. Still, there may be multiple explanations for such findings.

Sled towing training interventions have been widely used in senior populations and are associated with enhancing speed development (Cross et a. 2017; Alcaraz et al. 2018) along with other physical attributes (e.g., force and velocity; Cross et al. 2017; Morin et al. 2017). However, the literature on the effect of sled towing in youth athletes is less developed. To the authors' knowledge, only one other study has considered maturity status and a 6-week sled intervention in elite youth athletes (Rumpf et al. 2015). The current findings for Pre-PHV are consistent with Rumpf et al. (2015) where no changes were observed following the 6-week intervention. At the same time, the P-values (probability values) associated with the Pre-PHV is around 0.80 which can be interpreted as 80% chance that the variables were greater in T2 and 20% chance they were lower. In its first instance, this seems like a positive change; however, all the variables with a P-value around 0.8, are associated with high uncertainty, and therefore, a real effect following the intervention is unlikely (associated high percentages of RTM) for the Pre-PHV group. However, Rumpf et al. (2015) reported significant improvements for the combined group (Circa-Post-PHV), which is in contrast to the current study’s findings. The authors failed to discuss mechanisms as to why the Pre-PHV failed to show any improvements but elude to a potential maturity-related response for the combined group.

The current findings appear to suggest that prepubertal boys may not improve physical qualities by sled towing that uses maximum BM loads of 30%. The loads used in the present study were heavier than those of the Rumpf et al. (2015) (10 vs. 30% respectively) and were heavily influenced by the recent shift in philosophy for increased loading paradigms (Cross et al. 2017). As such, very heavy sled loads have been shown to enhance athletic performance in senior athletes (Cross et al. 2017; Morin et al. 2016) with loads around 69-89% BM to be used. The current study aimed to advance from the loads used in the Rumpf et al. (2015), given their non-significant findings for the Pre-PHV group, while considering there may be an increased risk in injury with loads as high as 89% BM in youth athletes. While position statements advocate for the use of heavy loads in youths (Lesinski et al. 2016), given the limited empirical evidence surrounding sled towing in youth athletes, caution must proceed until evidence is provided demonstrating the use of heavier loads is safe. However, the sled loads used for the Pre-PHV group may not have been appropriate, and, likely, the training impetus was not maturity-specific. For instance, when we consider the impact maturation has on physical development, it is believed that maturity-dependant response may occur following a specific intervention, which may be indicative of ‘synergistic adaptation’ (Radnor et al. 2018). A ‘synergistic adaptation’ refers to the symbiotic relationship between specific adaptations of an imposed training demand and concomitant growth and maturity-related adaptations (Lloyd et al. 2016). Whilst, Van Hooren and De Ste Croix (2002) question the validity of ‘sensitive periods’ for specific physical qualities, it certainly does not detract from the notion of a ‘synergistic adaptation’ following interventions in youth athletes. For example, it is not uncommon for prepubertal athletes to improve physical performance (mainly) through neuromuscular improvements (Peña-González et al. 2019) due to the plasticity of the central nervous system (Viru et al. 1999). As such, plyometric training is believed to induce changes in motor unit recruitment, contraction velocity, preactivation and a greater reliance on the short-latency stretch reflex, resulting in a more feed-forward SSC function in prepubertal youth athletes (Radnor et al. 2018). Thus, plyometric training creates the ideal maturity-dependent impetus to achieve the desired 'synergistic adaptation' specific for this maturity group.

Although sled towing may be a cyclical movement with SSC function (similar to that of a plyometric), adaptations following plyometric training are determined by the rate of the pre-stretch (i.e. the eccentric phase) of the activity. Therefore, it is likely the sled loadings were too heavy, increasing ground contact time (GCT) (Alcaraz et al. 2018), which would reduce the pre-stretch (eccentric phase) and therefore limit the neurological signal sent from the muscle spindle reducing the shortening cycle of the plyometric movement (Davies et al. 2015). This primarily denotes the term plyometric and changes the exercise impetus and is not the desired effect to achieve the 'synergistic adaptation' for the Pre-PHV boys (Radnor et al. 2018). Although GCT was not measured in the current study, it is plausible the lack of observed effects are a consequence of the loads used along with a range of other factors (e.g., concurrent training of soccer practice, increase stride length as a consequence of the sled load) and inherently do not create the ideal training impetus to reap the benefits for a 'synergistic adaptation'. It has also been established that youths of differing maturity status could respond to sprint training (Moran 2017; Moran et al. 2018). A recent meta-analytical review showed far larger effects in postpubertal ($d = 1.39$) and pubertal ($d = 1.15$) athletes than in prepubertal ($d = -0.18$) boys (Moran et al. 2018) indicating a maturity-specific adaptation.

Similar to the Pre-PHV group, both the Circa- and Post-PHV groups failed to improve following the sled intervention. Although high P-values (for example $P = 0.8$) have been reported for rImp300, this 80% probability is associated with a higher percentage of RTM of 36%. Therefore, there is uncertainty associated with these positive improvements. These findings are different from those reported by Rumpf et al. (2015) who reported a moderate improvement of around 6% in the combined Circa- and Post-PHV in 30 m sprint time. However, the methodologies employed by Rumpf et al. (2015) to investigate the impact of sled towing on other qualities should be scrutinised and have been discussed previously. Finally, the combined group is not a true representation of a 'synergistic adaptation' as both Circa- and Post-PHV groups will respond differently to a given bout of training or specifically to sprint training (Moran et al. 2018). For example, Morris et al. (2018a) demonstrated a Circa-PHV group had superior physical development across a football season, compared to the Pre- and Post-PHV groups. By Rumpf et al. (2015) combining maturity groups, information around maturity specific adaptations and the potential 'synergistic adaptation' is not clear. Although the current study's findings reveal no impact, it has demonstrated those findings for each maturity group.

While the current study examined the impact of sled towing across a range of maturity status' using a variety of practical assessment methods (IMTP, CMJ) including gold-standard techniques (e.g., force platforms), thus adding practical value to the paediatric literature. It is not without limitations. Firstly, limitations can exist for the classification of maturity status using the Mirwald equation (Lloyd et al. 2014). As such, some of the players may have been misclassified into the incorrect maturity group given the associated error and close overlap of the group bandwidths. The authors acknowledge these limitations, but it was the most practical assessment available. Secondly, the lack of improvements observed in the current findings across the maturity groups, and the conflicting evidence reported by Rumpf et al. (2015), maybe a consequence of the methodology used to determine the sled towing loadings in the current study. Although the prescription of %BM method is practical and heavily cited (Petrakos et al. 2016), it is now under scrutiny (Cahill et al. 2019a; Cross et al. 2017). When using %BM prescription, although the load is standardised using BM, everyone will display different velocity decrements based on the same %BM loading (Cahill et al. 2019b; Cross et al. 2017). For example, one athlete may show a decrement of 20% compared to a 40% decrement in another athlete with the same loading creating a non-standardised effect (Cahill et al. 2019a). In addition, Cahill et al. (2019b) investigated the load-velocity relationship and established that 50% decrement is achieved ~89% BM to target the Pmax zone in high-school athletes but reports a large variance (95% CI 71–107% BM). This concept is derived from senior populations (Morin et al. 2017; Cross et al. 2017), and Cahill et al. (2019b) follow the recommendations that a decrement of 50% is the optimum range to enhance accelerative capacity (Pmax zone), but warrants further investigation when we consider maturity status. Furthermore, the positive findings from Rumpf et al. (2015), compared to the current study, maybe a consequence of the specificity of testing to training. This principle has been shown in youth athletes (Behm et al. 2017) and could explain why the current study has not demonstrated a positive effect following the intervention. Also, the length of the intervention (minimum of 10 sessions) may have aslo contributed to the lack of findings. For example, Moran et al. (2017) has demonstrated an increase in performance is attributed to where interventions last longer than 8 weeks (Moran et al. 2017). It is plausible the length of the current studies intervention was inadequate. The limited evidence in elite youth populations makes it hard to understand the maturational effect on sled performance. The recent study by Cahill et al. (2019b) identifies a load-velocity relationship with a population of Post-PHV athletes and in high-school males. Although, the authors use the narrative ‘youth athletes’ their population has a mean age of 16.7±0.9 years and a mean YPHV of 1.8±0.8 years. Therefore, the broader application of the load-velocity relationship to Pre- and Circa-PHV requires investigation. This study not having a control group is also a limitation. Inclusion of a control group would substantiate the findings (or lack of) for those who have received the treatment (in this instance, the sled towing intervention). Finally, understanding kinematic and kinetic changes during sprinting would provide greater clarity surrounding the specific maturity-related changes more so than the generic testing battery currently used in the study. Future studies should look to include specific testing-training protocols (Behm et al. 2017) when moniroting changes from a sled towing intervention.

CONCLUSION

This study evaluated the impact a 6-week sled towing intervention on speed, lower body power and strength in youth soccer players across Pre-, Circa- and Post-PHV maturity groups. Findings demonstrated that the sled intervention had minimal impact on the performance measures irrespective of maturity group. However, the results also revealed that none of the performance measures declined over the six weeks. Practically, sled towing may not be an effective strategy to improve physical performance, regardless of maturity status when used in isolation. These findings are likely to be a consequence of the loadings used (and the methodology used to determine such loadings; testing to training was not specific) coupled with the influence of maturation and the length of the intervention (only 6-weeks). For example, the desired 'synergistic adaptation' or maturity-related changes were not responsive to the loadings used (10-30% BM). The Pre-PHV group did not elicit any change which may be due to the inherent nature and reliance of force production required during sled towing which would not elicit changes in the neuromuscular properties, which are the maturity associated improvements in the group. Equally, those who were more mature also failed to improve performance with the increased loadings, which can increase strength, speed and power via neural and morphological adaptations. This study does warrant further investigation into heavier loadings for the Circa- and Post-PHV groups, while the Pre-PHV group should focus on interventions that aim to decrease GCT, which may be more related to the maturity-specific adaptations, such as plyometric training for long-term athletic development of youth athletes.

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Table 1 Descriptive parameters of Anthropometric measurements Pre and Post sled Training Intervention for all Maturity Groups.

	Pre-PHV (*n* = 25)		**Circa-PHV (*n* = 24)**		**Post-PHV (*n* = 24)**	
	Pre	**Post**	**Pre**	**Post**	**Pre**	**Post**
Age (years)	12.19 ± 0.51	12.38 ± 0.51	14.30 ± 0.84	14.42 ± 0.85	16.34 ± 1.18	16.47 ± 1.18
Years from PHV (years)	-1.97 ± 0.5	-1.88 ± 0.47	-0.15 ± 0.58	-0.11 ± 0.57	2.25 ± 1.01	2.27 ± 1.00
Height (cm)	150.88 ± 7.99	151.94 ± 7.75	164.87 ± 6.99	165.23 ± 6.82	179.38 ± 7.1	179.46 ± 7.02
Body Mass (kg)	41.53 ± 6.22	41.95 ± 6.16	53.92 ± 5.31	54.1 ± 5.28	71.74 ± 9.11	71.65 ± 9.29
Sitting Height (cm)	75.2 ± 3.24	75.63 ± 3.1	82.01 ± 3.08	82.16 ± 2.96	91.85 ± 4.95	91.89 ± 4.54
Leg Length (cm)	75.6 ± 5.73	76.3 ± 5.6	82.85 ± 4.93	83.07 ± 4.95	87.53 ± 4.28	87.57 ± 4.33

Note: PHV = Peak Height Velocity

Table 2 Pre and Post Descriptive Statistics (Mean ± SD) for the Performance Measures across maturity groups.

	Pre-PHV (*n* = 25)		**Circa-PHV (*n* = 24)**		**Post-PHV (*n* = 24)**	
	Pre	**Post**	**Pre**	**Post**	**Pre**	**Post**
10m (s)	1.94 ± 0.11	1.96 ± 0.10	1.84 ± 0.1	1.83 ± 0.11	1.75 ± 0.06	1.75 ± 0.05
30m (s)	4.90 ± 0.30	4.87 ± 0.30	4.53 ± 0.25	4.5 ± 0.27	4.2 ± 0.13	4.18 ± 0.11
CMJ Imp ($N.s^{-1}$)	99.7 ± 15.2	102.4 ± 27.5	139.2 ± 19.7	139.3 ± 21.2	196.7 ± 32.5	196.6 ± 31.9
JH (m)	0.28 ± 0.06	0.28 ± 0.07	0.31 ± 0.04	0.31 ± 0.05	0.36 ± 0.04	0.35 ± 0.03
Imp100 ($N.s^{-1}$)	20.7 ± 6.8	21.3 ± 7.0	32.8 ± 14.1	34.1 ± 13.8	50.0 ± 12.5	50.5 ± 19.3
rImp100 (N.s/Kg)	0.5 ± 0.2	0.5 ± 0.2	0.6 ± 0.3	0.6 ± 0.3	0.7 ± 0.2	0.7 ± 0.2
Imp300 ($N.s^{-1}$)	138.3 ± 42.2	150.6 ± 43.2	218.7 ± 75.9	218.9 ± 58.4	271.3 ± 1157	303.6 ± 66.1
rImp300 (N.s/Kg)	3.4 ± 1.1	3.6 ± 1.0	4.1 ± 1.4	4.1 ± 1	3.8 ± 1.6	4.2 ± 0.8
PF (N)	1197.0 ± 157.7	1239.8 ± 174.1	1638.6 ± 193.6	1669.3 ± 226.7	2318.0 ± 356.9	2296.3 ± 375.8
rPF (N/Kg)	28.9 ± 3.3	30.1 ± 4.6	30.5 ± 2.8	31.0 ± 3.8	32.3 ± 3.7	32.2 ± 4.3

Note; Mad = Median Absolute Deviation; CMJ = Counter Movement Jump; CMJ Imp = CMJ Impulse; JH = Jump Height (m); Imp100 = Impulse @100ms (N.s); rImp100 = Relative Impulse @100ms (N.s/Kg); Imp300 = Impulse @300ms (N.s); rImp300 = Relative Impulse @300ms (N.s/Kg); PF = Peak Force (N); rPF = Relative Peak Force (N/Kg).

Table 3 Pre and Post Descriptive Statistics (Median ± MAD) for the Performance Measures across maturity groups.

	Pre-PHV (*n* = 25)		**Circa-PHV (*n* = 24)**		**Post-PHV (*n* = 24)**	
	Pre	**Post**	**Pre**	**Post**	**Pre**	**Post**
10m (s)	1.95 ± 0.09	1.94 ± 0.1	1.84 ± 0.09	1.81 ± 0.08	1.76 ± 0.04	1.74 ± 0.04
30m (s)	4.89 ± 0.27	4.81 ± 0.3	4.52 ± 0.27	4.46 ± 0.21	4.21 ± 0.16	4.18 ± 0.11
CMJ Imp (N.s^{-1})	99.2 ± 14.0	95.1 ± 14.3	139.2 ± 18.8	138.0 ± 19.5	185.1 ± 23.7	192.4 ± 27.6
JH (m)	0.28 ± 0.06	0.27 ± 0.08	0.31 ± 0.06	0.31 ± 0.04	0.35 ± 0.04	0.35 ± 0.03
Imp100 (N.s^{-1})	19.1 ± 6.1	21.8 ± 5.4	29.7 ± 11.4	34.1 ± 14.5	51.2 ± 11.0	47.7 ± 15.2
rImp100 (N.s/Kg)	0.5 ± 0.2	0.5 ± 0.2	0.6 ± 0.2	0.7 ± 0.2	0.7 ± 0.2	0.7 ± 0.2
Imp300 (N.s^{-1})	144.3 ± 38.7	151.3 ± 58.5	211.8 ± 71.9	214.5 ± 55.8	303.2 ± 74.9	317.6 ± 62.8
rImp300 (N.s/Kg)	3.5 ± 0.9	3.7 ± 1.1	4.2 ± 1.1	3.9 ± 1.0	4.3 ± 0.8	4.1 ± 0.8
PF (N)	1248.1 ± 133.5	1249.9 ± 108.4	1591.2 ± 186.1	1618.2 ± 220.2	2313.2 ± 316.3	2272.1 ± 346.4
rPF (N.Kg^{-1})	28.5 ± 3.3	30.2 ± 3.9	30.3 ± 3.5	30.9 ± 4.6	32.0 ± 2.4	31.4 ± 4.2

Note; Mad = Median Absolute Deviation; CMJ = Counter Movement Jump; CMJ Imp = CMJ Impulse; JH = Jump Height (m); Imp100 = Impulse @100ms (N.s); rImp100 = Relative Impulse @100ms (N.s/Kg); Imp300 = Impulse @300ms (N.s); rImp300 = Relative Impulse @300ms (N.s/Kg); PF = Peak Force (N); rPF = Relative Peak Force (N/Kg)

Table 4 Bayesian T-test comparing Pre and Post-scores for Pre-PHV (*n* = 25) maturity group following a 6-week sled intervention with estimated mean data.

Measure	**Estimated Difference**	**Estimated Sigma**	**HDI's**	**P>0**	**P<0**	**ES**	**RTM (%)**
10m (s)	0.01	1.08	-0.05, 0.08	0.69	0.31	0.15 (-0.45, 0.68)	56
30m (s)	-0.03	1.30	-0.21, 0.15	0.37	0.63	-0.11 (-0.69, 0.49)	56
CMJ Impulse (N.s)	-0.75	12.31	-9.25, 7.95	0.42	0.58	-0.1 (-0.76, 0.58)	26
Jump Height (m)	0.00	1.27	-0.04, 0.04	0.44	0.56	-0.05 (-0.64, 0.53)	18
Impulse 100 ms (N.s)	0.56	1.27	-3.39, 4.56	0.61	0.39	0.07 (-0.47, 0.67)	55
Relative Impulse 100 ms (N.s/Kg)	0.01	1.11	-0.1, 0.13	0.59	0.41	0.08 (-0.49, 0.68)	43
Impulse 300 ms (N.s)	10.84	1.27	-14.56, 36.98	0.80	0.20	0.27 (-0.29, 0.86)	40
Relative Impulse 300 ms (N.s/Kg)	0.25	1.95	-0.33, 0.82	0.80	0.20	0.26 (-0.35, 0.86)	51
Peak Force (N)	40.19	150.99	-55.99, 132.86	0.79	0.21	0.25 (-0.33, 0.82)	30
Relative Peak Force (N·Kg-1)	1.16	4.56	-1.09, 3.42	0.85	0.15	0.31 (-0.31, 0.87)	54

Note; Estimated Difference = Estimated difference between pre and post-performance; Estimated Sigma = Combined pre and post variation of estimated difference; HDI's = 95% Higher Density Intervals; P>0 = Probability greater than 0; P<0 = Probability less than 0; ES = Standardised effect size; RTM % = Regression to the mean.

Table 5 Bayesian T-test comparing Pre and Post-scores for Circa-PHV (*n* = 24) maturity group following a 6-week sled intervention with estimated mean data.

Measure	**Estimated Difference**	**Estimated Sigma**	**HDI's**	**P>0**	**P<0**	**ES**	**RTM (%)**
10m (s)	-0.01	1.22	-0.07, 0.05	0.40	0.6	-0.09 (-0.66, 0.51)	56
30m (s)	-0.03	1.32	-0.18, 0.13	0.36	0.64	-0.12 (-0.77, 0.46)	45
CMJ Impulse (N.s)	-0.04	20.17	-11.86, 12.39	0.49	0.51	-0.01 (-0.59, 0.61)	30
Jump Height (m)	0.00	1.13	-0.02, 0.03	0.63	0.37	0.08 (-0.46, 0.69)	23
Impulse 100 ms (N.s)	1.63	14.72	-6.56, 9.8	0.65	0.35	0.12 (-0.48, 0.77)	43
Relative Impulse 100 ms (N.s/Kg)	0.03	1.23	-0.13, 0.18	0.63	0.37	0.12 (-0.51, 0.67)	45
Impulse 300 ms (N.s)	-3.7	68.82	-41.83, 35.99	0.42	0.58	-0.05 (-0.67, 0.54)	38
Relative Impulse 300 ms (N.s/Kg)	-0.11	2.06	-0.85, 0.62	0.80	0.2	-0.1 (-0.75, 0.48)	36
Peak Force (N)	29.13	189.81	-98.18, 153.61	0.68	0.32	0.14 (-0.43, 0.73)	20
Relative Peak Force (N·Kg-1)	0.46	4.14	-1.53, 2.55	0.67	0.33	0.14 (-0.46, 0.72)	25

Note; Estimated Difference = Estimated difference between pre and post-performance; Estimated Sigma = Combined pre and post variation of estimated difference; HDI’s = 95% Higher Density Intervals; P>0 = Probability greater than 0; P<0 = Probability less than 0; ES = Standardised effect size; RTM % = Regression to the mean.

Table 6 Bayesian T-test comparing Pre and Post-scores for Post-PHV (*n* = 24) maturity group following a 6-week sled intervention.

Measure	**Estimated Difference**	**Estimated Sigma**	**HDI's**	**P>0**	**P<0**	**ES**	**RTM (%)**
10m (s)	0.00	0.90	-0.03, 0.03	0.51	0.49	0.01 (-0.58, 0.6)	36
30m (s)	-0.01	0.97	-0.09, 0.06	0.35	0.65	-0.12 (-0.72, 0.47)	13
CMJ Impulse (N.s)	-0.21	31.85	-19.18, 18.9	0.49	0.51	-0.08 (-0.66, 0.52)	4
Jump Height (m)	0.00	0.80	-0.03, 0.02	0.36	0.64	-0.12 (-0.75, 0.53)	30
Impulse 100 ms (N.s)	-0.88	13.20	-9.93, 8.2	0.42	0.58	-0.09 (-0.69, 0.56)	95
Relative Impulse 100 ms (N.s/Kg)	-0.02	1.18	-0.15, 0.11	0.38	0.62	-0.08 (-0.71, 0.5)	97
Impulse 300 ms (N.s)	24.41	108.36	-29.16, 79.86	0.81	0.19	0.19 (-0.44, 0.82)	97
Relative Impulse 300 ms (N.s/Kg)	0.32	2.00	-0.4, 1.09	0.78	0.22	0.14 (-0.54, 0.77)	81
Peak Force (N)	-19.37	366.09	-240.24, 203.69	0.42	0.58	-0.08 (-0.66, 0.52)	27
Relative Peak Force (N·Kg-1)	-0.29	4.57	-2.46, 1.96	0.38	0.62	-0.09 (-0.69, 0.56)	53

Note; Estimated Difference = Estimated difference between pre and post-performance; Estimated Sigma = Combined pre and post variation of estimated difference; HDI's = 95% Higher Density Intervals; P>0 = Probability greater than 0; P<0 = Probability less than 0; ES = Standardised effect size; RTM % = Regression to the mean.

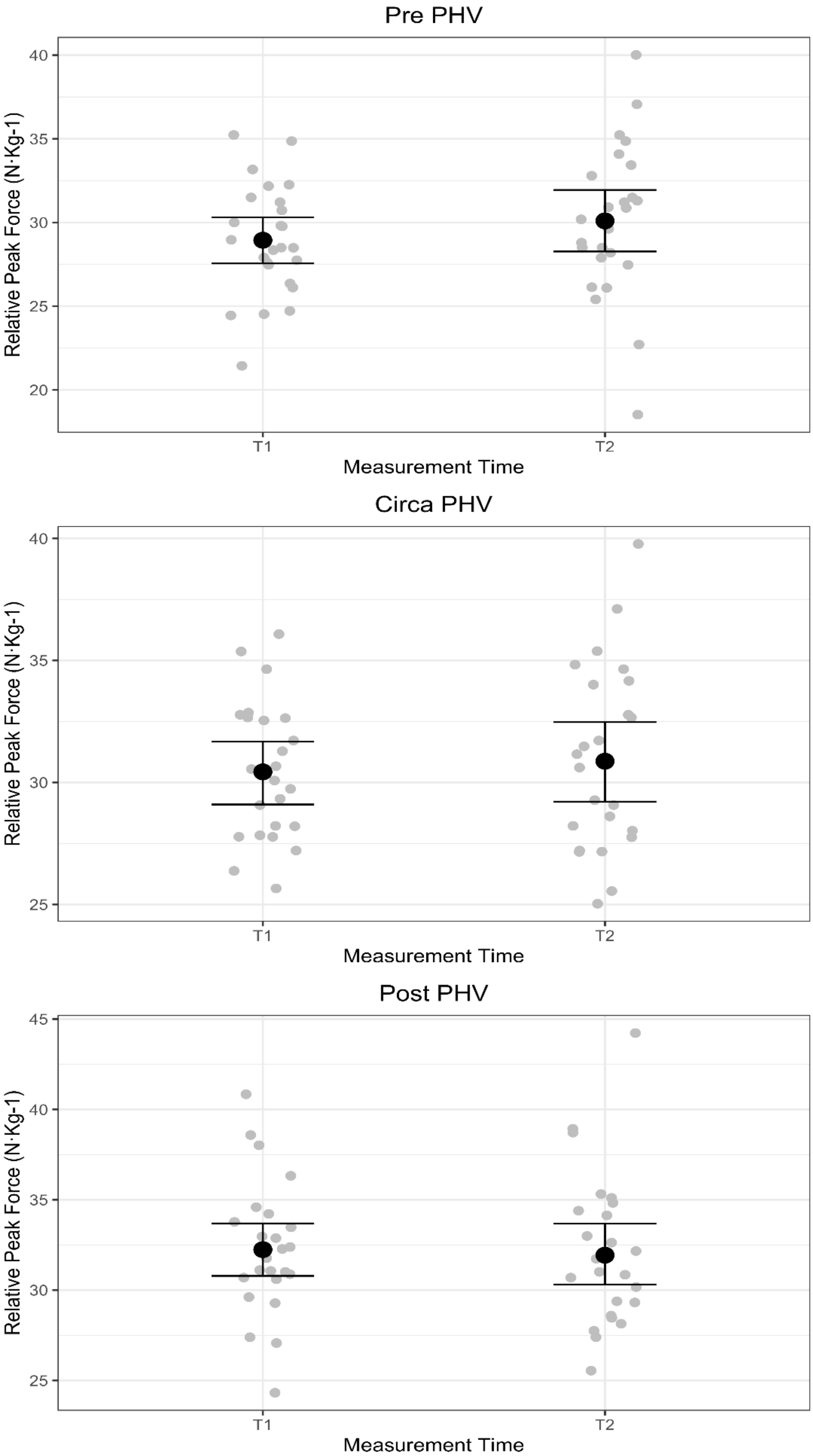

Figure 1 Relative Strength Pre and Post-scores for Pre-, Circa- and Post-PHV maturity groups following a 6-week sled intervention.

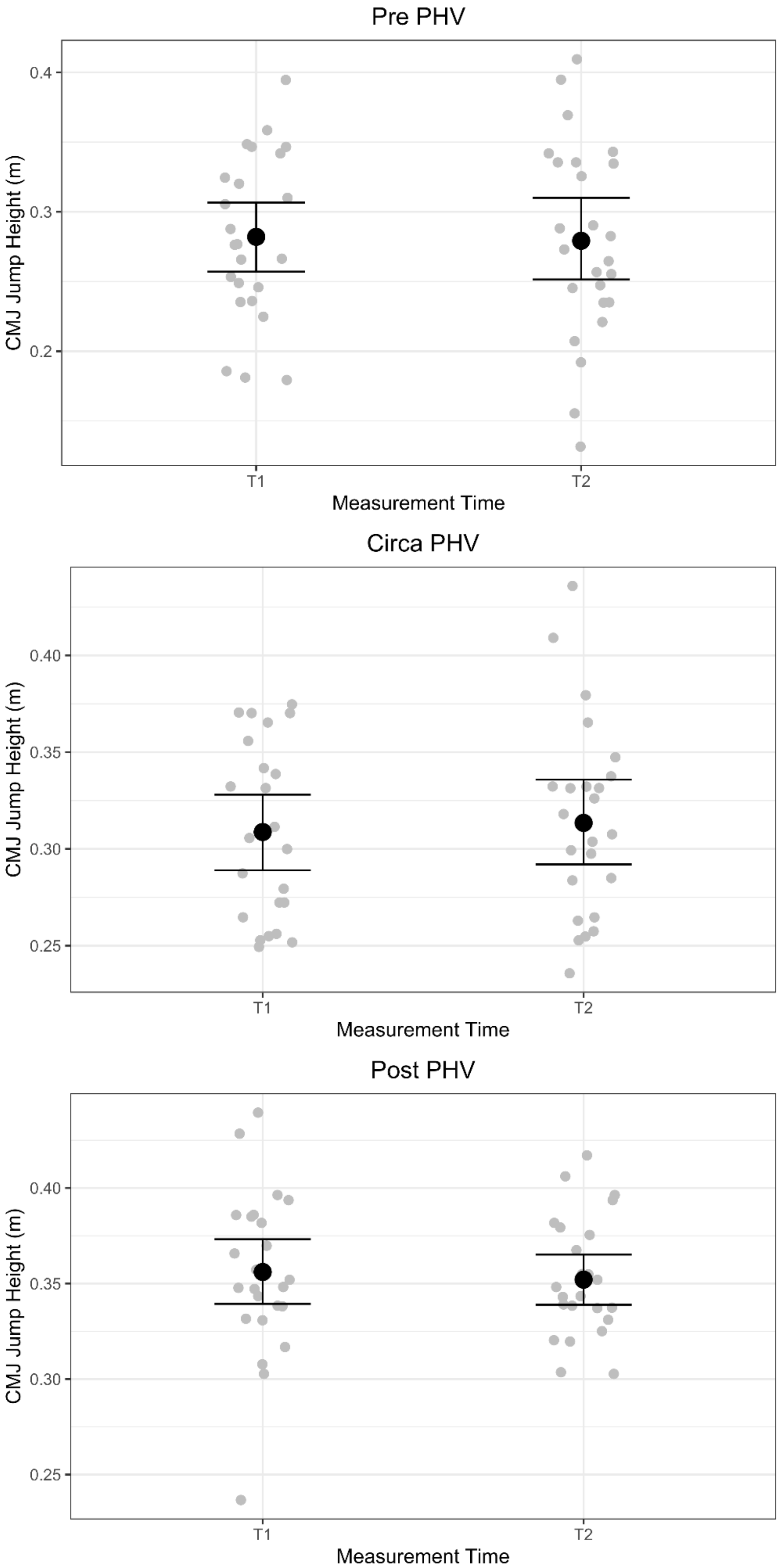

Figure 2 Countermovement Jump Height Pre and Post-scores for Pre-, Circa- and Post-PHV maturity groups following a 6-week sled intervention.

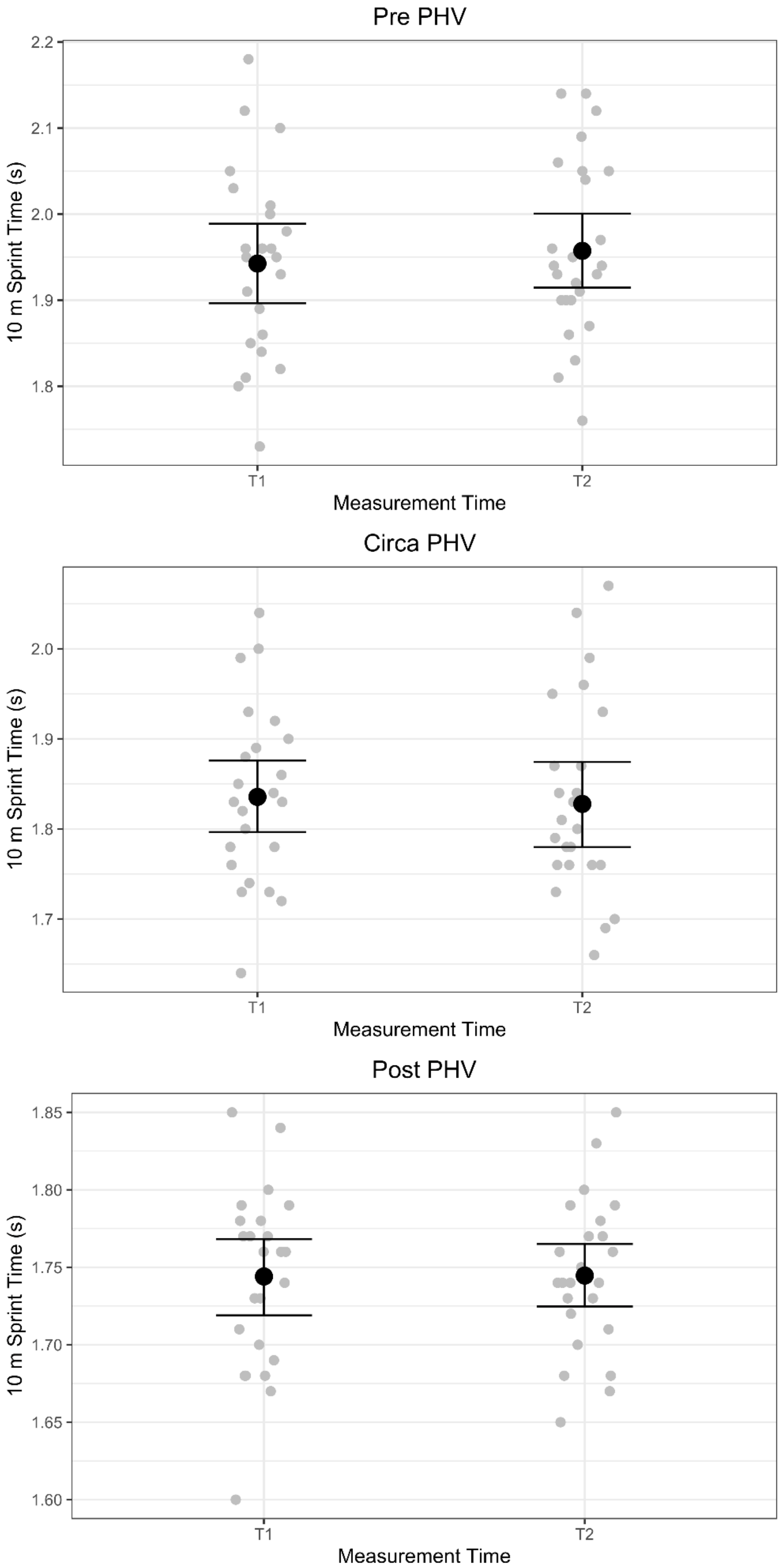

Figure 3 10 m Sprint times Pre and Post-scores for Pre-, Circa- and Post-PHV maturity groups following a 6-week sled intervention.