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Multiple risk factors associated with lumbar bone stress injury in youth cricket fast bowlers

Kevin Sims[1 *], Richard Saw[2], Anna E. Saw[1], Alex Kountouris[1, 3], John W. Orchard[1]

[1]*Cricket Australia, VIC, Australia*
[2]*Australian Institute of Sport, ACT, Australia*
[3]*La Trobe Sport and Exercise Medicine Research Centre, La Trobe University, VIC, Australia*

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A B S T R A C T

To investigate the relative influence of multiple risk factors on the development of lumbar bone stress injury in a cohort of youth cricket fast bowlers. Injury data from five consecutive cricket seasons was retrospectively reviewed to determine which of a group of 222 high level youth male cricket fast bowlers (age 17.4 ± 1.1 years) sustained a lumbar bone stress injury. This information was then combined with measures related to age, anthropometry, musculoskeletal screening, physical fitness, bowling volume and bowling technique for use in a multivariate binary logistic regression analysis of risk factors for lumbar bone stress. There were 49 lumbar bone stress injuries in the cohort. Multivariate analysis identified a younger age ($p < 0.001$), a taller height ($p = 0.011$), and a faster bowling speed ($p = 0.022$) as significant risk factors for lumbar bone stress injury. The multivariate model was able to explain 36% of the variance (Nagelkerke $R^2 = 0.36$). The risk of injury was 2.99 times higher for every year younger, 1.1 times higher for every centimetre taller, and 1.1 times higher for every km/h faster bowling speed. A younger, taller, faster bowler was the profile for a bowler at increased risk of lumbar bone stress injury in our study. However, it was evident that other factors not included in the current study also play a significant role in the aetiology of a lumbar bone stress injury.

1. Introduction

In the game of cricket, the prevalence of injuries to fast bowlers is approximately three times higher than other players in a team (Orchard, Kountouris, & Sims, 2016). Fast bowlers are particularly susceptible to lumbar bone stress injury (stress reaction (bone oedema with no cortical breach) or stress fracture (bone oedema with cortical breach)), with reported incidence varying between 11-33% (Crewe, Elliott, Couanis, Campbell, & Alderson, 2012; Foster et al., 1989; Kountouris et al., 2019). Lumbar bone stress injury (LBSI) accounts for the greatest time lost to injury in cricketers (Orchard et al., 2016), with recovery periods in the order of 6-8 months (Alway, Brooke-Wavell, Langley, King, & Peirce, 2019; Ranson, Burnett, & Kerslake, 2010). Younger fast bowlers (< 22 years of age) appear to be particularly at risk, being three to four times more likely to suffer a bone stress injury (predominantly lumbar spine) than their older counterparts (Alway, Brooke-Wavell, et al., 2019; Blanch, Orchard, Kountouris, Sims, & Beakley, 2015).

Purported risk factors for LBSI include specific biomechanical factors related to bowling technique such as higher shoulder counter-rotation and trunk lateral flexion (Bayne, Elliott, Campbell, & Alderson, 2016; Portus, Mason, Elliott, Pfitzner, & Done, 2004; Ranson, Burnett, King, Patel, & O'Sullivan, 2008). Higher volumes of bowling are associated with injury (Alway, Brooke-Wavell, et al., 2019; Dennis, Farhart, Goumas, & Orchard, 2003), with the lumbar spine likely susceptible to repetitive loading due to large vertical ground reaction forces (Bayne et al., 2016) and high intervertebral shear forces (Crewe, Campbell, Elliott, & Alderson, 2013) associated with fast bowling.

Physical preparation is considered to be an important component to injury prevention in fast bowlers (Forrest, Scott, Hebert, & Dempsey, 2018), although there is limited evidence linking LBSI to physical deficits. A reduction in sit and reach distance has been identified in youth fast bowlers with disc degeneration (Elliott, Hardcastle, Burnett, & Foster, 1992), and a greater quadriceps torque in the front foot of bowlers who suffered a lumbar spine stress fracture (Foster et al., 1989). A more recent

*Corresponding Author: Kevin Sims, Cricket Australia, Australia, k.sims@qsmc.net.au

prospective study identified a reduction in lumbar extensor muscle endurance and greater medial knee movement in a single leg decline squat in youth fast bowlers who subsequently sustained a low back injury including stress fracture (Bayne et al., 2016). Evidence from predominantly college age female populations suggest excessive medial knee movement during the squat task may be related to hip abduction and external rotation muscle weakness (Cashman, 2012; Powers, 2010; Stickler, Finley, & Gulgin, 2015; Willy & Davis, 2011). Therefore, there may then be a link between hip muscle weakness and the development of LBSI, however to date there is no direct evidence supporting this as a possible risk factor.

The development of LBSI is clearly multi-factorial, yet the majority of published fast bowling injury research has tended to focus on broader risk areas such as workload and technique in isolation. The studies that have looked at multiple risk factors have either had small numbers (Bayne et al., 2016) or did not use multivariate analysis (Foster et al., 1989). This has made it difficult to understand the relative contribution of individual risk factors to the overall injury risk. The aim of this study was to investigate the relationship between LBSI and combinations of risk factors encompassing workload, technique and physical preparedness in youth fast bowlers.

2. Methods

Ethics approval was attained from the La Trobe University Human Research Ethics Committee (HEC20058). Data were retrieved from Cricket Australia's online database (Athlete Management System, Fair Play Pty Ltd.).

2.1. Participants

Two hundred and twenty-two Australian youth male fast bowlers (17.4 ± 1.1 years, range 15.1-19.7) participated in elite pathway programs over five seasons (2015-20, season from July to March). A fast bowler is defined as a bowler who has a fast run up, delivers the ball at a medium-to-fast pace, and to which the wicket keeper typically stands back from the stumps. Bowlers were included if: 1) they were medium-to-fast bowlers as classified by their state cricket program; 2) they were members of their respective state under-17 or under-19 cricket programs; 3) prior to the season had received a musculoskeletal screening; and; 4) had bowling volume recorded; Bowlers who met the inclusion criteria for more than one season were included once using the season with the most recent bowling technique assessment and physical fitness assessment.

Bowlers were classified as 'injured' or 'not injured' based on whether they had a LBSI diagnosed that season. A LBSI was diagnosed if an MRI identified a stress reaction (bone oedema with no cortical breach) or stress fracture (bone oedema with cortical breach) (Kountouris et al., 2019) and the player was subsequently classified by medical staff as unavailable to train or play.

2.2. Procedures

2.2.1. Musculoskeletal screening and physical fitness assessment

The screening process consisted of a series of standardised tests undertaken in each of the six State Cricket Associations in Australia between June and October prior to the start of the respective season. The tests included height, weight, ankle dorsiflexion range of motion, hip internal and external range of motion, lumbo-pelvic stability test and the Biering Sorenson test which have all been previously described (Bayne et al., 2016). Other tests included the Star Excursion Balance Test (SEBT) (Hertel, Braham, Hale, & Olmsted-Kramer, 2006; Plisky, Rauh, Kaminski, & Underwood, 2006), lateral trunk flexion range of motion test (Nealon & Cook, 2018) and hip abduction and extension strength measures (Thorborg, Petersen, Magnusson, & Hölmich, 2010). When a test involved assessing both limbs it was delineated as front foot (FF-the foot contralateral to the bowling arm) or back foot (BF-the foot ipsilateral to the bowling arm). Physical fitness was assessed with a running two-kilometre time trial (2km TT) performed on flat ground.

2.2.2. Bowling volume

The number of balls bowled per day in training and matches was recorded daily by the bowler with staff oversight in a specialised database with mobile application interface. Bowling intensity was not measured. Bowling loads (volume and frequency) were calculated as averages over one, four, and 12-week windows during the period 1 October to 31 December. If a bowler sustained a LBSI before the end of December their average bowling loads (using the one, four, and 12-week windows) were calculated up to the date of injury. If a LBSI was sustained after December, the bowling loads were calculated as of December 31. This was done due to confidence that the data recorded during the period of October to December was accurate due to close monitoring of compliance by staff as players prepared for the respective Cricket Australia age group national championships and later season LBSI are likely to be related to prolonged overuse during the season (Alway, Brooke-Wavell, et al., 2019). Fifty-two-week bowling load was calculated up to the day of injury or end of season (31 March) in the uninjured group.

2.2.3. Technique assessment

Two-dimensional (2-D) bowling technique assessment was performed by national staff at each of the State Cricket Associations between February and October each year (i.e., at the end of one season or the beginning of the next). Assessment involved the bowler bowling 18 deliveries in a netted environment, each delivery aimed at a specific area on the wicket. Tests were recorded with high speed cameras (Basler Aca2000 – 165uc) operating at 150 frames per second. Vision was captured from a tripod 1.5m high, directly in line and 25m behind middle stump at the bowlers end of the pitch. The ball speed was also captured with a radar (Stalker Pro II radar, 34.7 GHZ) mounted in the same position as the high speed camera on a stand 1.6m high. The maximum ball speed achieved in the session was used in the subsequent analysis. Six balls to three specific regions of the pitch were then selected for analysis by an experienced sports scientist. The vision was analysed and placed in ranges of shoulder counter-rotation and trunk lateral flexion representing low (0-25 deg), moderate (25-40 deg) and high (> 40 deg) categories. These measures have previously been described as part of bowling biomechanical assessment and have been linked to injury in three-dimensional analyses.(Bayne et al., 2016; Portus et al., 2004) In a small number of cases (n = 7) where 3D analysis was available it was used. The method of data capture has been previously described (Portus et al., 2004) and the same testing procedure was followed as per the 2D testing except that it was indoor. The shoulder counter-rotation and lateral flexion variables were then categorised with respect to the three groups described above. The majority of the bowling screening (n = 101/150) was done in the same season (between July and March) or the previous season (31/150) as the bowling loads and musculoskeletal screening but in some cases it was not possible. In this situation if a screening was available within 2 years of the relevant season it was used in the analysis.

2.3. Statistical procedures

Univariate analyses were performed using simple logistic regression to identify variables from each of the measured factors (age, musculoskeletal screening and physical fitness, bowling volume, technique) which were significantly different between the injured and non-injured groups ($p < 0.05$). The initial analysis was then used as part of the decision making to identify variables to include in multivariate analysis. A hierarchical approach was also used to include variables that were not significantly different but based on previous research were thought to be relevant. Data used in the multivariate analysis were checked for multi-collinearity. The analysis involved a binary logistic regression (method: enter) with injury as the dependent variable and non-injured bowlers acting as the control. Contributing variables included in the model included: age at start of the season, height, star excursion balance test, average number of days bowled per week, 2km TT time, maximum ball speed, and shoulder counter-rotation. To simplify analysis, shoulder counter-rotation and trunk lateral flexion were dichotomised into two groups (< 40 degrees and > 40 degrees) as values > 40 degrees have been associated with LBSI (Bayne et al., 2016; Portus et al., 2004). Lumbo-pelvic control was dichotomised into level 0-1 and level 2-5 as previous research has shown very low values on the scale are related to LBSI (Bayne et al., 2016). Analysis was completed using SPSS (version 25, IBM, Armonk, NY, USA). The process from identification to analysis is outlined in Figure 1.

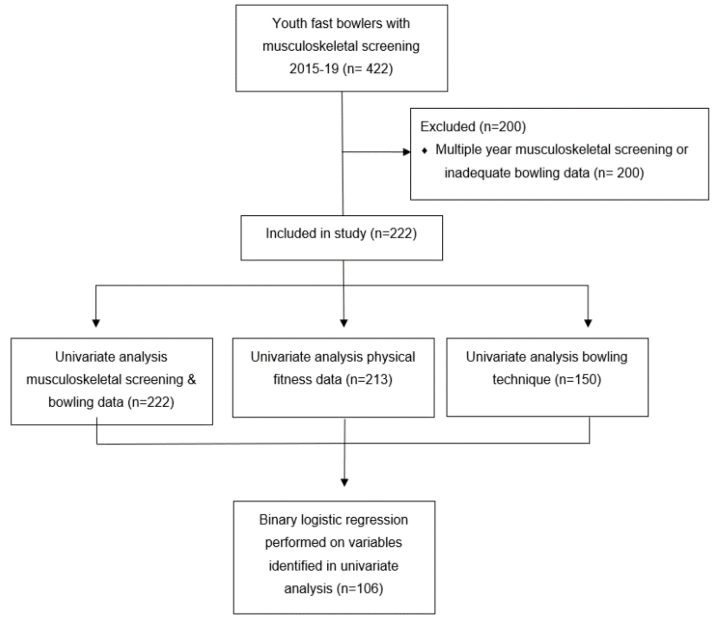

Figure 1: Flow diagram showing process from identification of subjects to analysis of data

3. Results

In total 49 of the 222 bowlers sustained a LBSI. Univariate analyses identified injured bowlers were younger ($p = 0.005$) and taller ($p = 0.007$) than their non-injured counterparts. Injured bowlers also performed less efficiently on the SEBT (FF $p = 0.006$, BF $p = 0.005$), and on average bowled more days per one week ($p = 0.009$), 4 weeks ($p = 0.042$) and 12 weeks ($p = 0.008$) than the non-injured group (Table 1). There was no difference between the two groups in bowling technique analysis (Table 2).

For the multivariate analysis, age, height and SEBT BF (only one SEBT was used as the FF and BF measures were highly correlated) were used based on the significant differences in the simple logistic regression analysis. The workload measures were all highly correlated (Pearsons r > 0.9) and therefore only the one-week average days per week measure was chosen as it had a similar effect size and more data in the LBSI group than the 12-week average days measure (some of the LBSIs occurred with less than 12 weeks of bowling load). In addition to these variables, the 2 km TT (poor aerobic fitness has been linked to lower limb injury in the military) (Tomes, Sawyer, Orr, & Schram, 2020), maximum ball speed (higher speeds are associated with greater lumbar forces (Crewe et al., 2013) and shoulder counter-rotation (high shoulder counter-rotation has been linked to LBSI) (Portus et al., 2004) were also included. The Nagelkerke R^2 value for the analysis was 0.36 and the results of the regression analysis are detailed in Table 3.

Table 1: Univariate analyses of continuous variables

	Injured	n	Not Injured	n	*p*	Effect size
Age (years)*	17.0 (1.0)	49	17.5 (1.1)	173	0.005	0.48
Height (cm)*	188.9 (5.8)	48	186.1 (6.2)	169	0.007	0.47
Weight (kg)	81.7 (8.8)	47	80.2 (7.9)	168	0.240	
Star Excursion Balance Test FF (cm)*	99.1 (6.9)	35	103.6 (8.2)	103	0.006	0.59
Star Excursion Balance Test BF (cm)*	98.8 (6.7)	35	103.6 (8.5)	103	0.005	0.63
Ankle dorsiflexion lunge FF (cm)	11.6 (3.3)	39	11.4 (3.2)	120	0.755	
Ankle dorsiflexion lunge BF (cm)	12.0 (3.0)	39	11.8 (3.4)	120	0.704	
Lateral trunk flexion FF (% leg length)	0.74 (0.03)	38	0.75 (0.05)	116	0.138	
Lateral trunk flexion BF (% leg length)	0.74 (0.02)	38	0.75 (0.05)	116	0.099	
Hip internal rotation FF (deg)	36 (8.6)	20	38 (13.0)	72	0.578	
Hip internal rotation BF (deg)	35 (10.7)	20	38 (11.2)	72	0.303	
Hip external rotation FF (deg)	52 (10.7)	20	50 (13.1)	72	0.631	
Hip external rotation BF (deg)	52 (8.8)	20	49 (13.3)	72	0.405	
Prone extension hold (sec)	130 (31)	27	129 (39)	124	0.844	
Hip abduction FF (% body weight)	0.25 (0.04)	43	0.26 (0.06)	154	0.342	
Hip abduction BF (% body weight)	0.25 (0.04)	43	0.26 (0.06)	153	0.623	
Hip extension FF (% body weight)	0.39 (0.08)	41	0.41 (0.1)	148	0.324	
Hip extension BF (% body weight)	0.40 (0.09)	41	0.43 (0.1)	149	0.173	
2 km time trial (mins)	7 min 41 secs (38 secs)	46	7 min 48 secs (38 secs)	167	0.260	
Total # of balls 52 weeks	2749 (1171)	49	2557 (1151)	172	0.310	
Total bowling days 52 weeks	77.5 (31)	49	69.6 (29)	172	0.100	
Average # of balls 1 week	85 (24)	49	76 (38)	170	0.120	
Average # of balls 4 weeks	350 (102)	49	324 (167)	170	0.290	
Average # of balls 12 weeks	1057 (293)	45	922 (458)	170	0.650	
Average days bowling 1 week*	2.3 (0.6)	49	2.0 (0.9)	170	0.009	0.48
Average days bowling 4 weeks*	9.5 (2.4)	49	8.2 (4)	170	0.042	0.39
Average days bowling 12 weeks*	28.3 (7.4)	45	23.6 (11.1)	170	0.008	0.50
Max Ball Speed (km/h)	123.1 (5.7)	35	121.6 (6)	115	0.190	

Note: * $p < 0.05$

Table 2: Cross tabulation tables and univariate regression analysis of categorical variables.

		Injured	Not injured	*p*
Lumbo-pelvic control	Level 0 or 1	4	28	0.171
	Level 2-5	42	136	
Shoulder counter-rotation	≤ 40 deg	15	65	0.281
	> 40 deg	19	54	
Lateral trunk flexion (max)	≤ 40 deg	19	50	0.154
	> 40 deg	15	69	

Table 3: Multivariate analyses of possible risk factors of lumbar bone stress injury in youth cricket fast bowlers (n = 106).

	Exp (B)	*p*
Age (years)*	0.334 (0.184-0.605)	0.000
Height (cm)*	1.122 (1.027-1.226)	0.011
Star Excursion Balance Test BF (cm)	0.944 (0.883-1.01)	0.097
Average days bowling 1 week	2.032 (0.874-4.726)	0.100
2 km time trial (min)	0.448 (0.179-1.121)	0.086
Max ball speed (km/h)*	1.115 (1.016-1.225)	0.022
Shoulder counter-rotation (deg)	1.142 (0.394-3.309)	0.807
Constant	0.001	0.534

Data presented as Exp (B) (lower and upper 95% confidence intervals). BF = back foot. * $p < 0.05$

Three variables were identified as risk factors with the risk of LBSI being 2.99 (1/0.334) times higher for every year younger in our cohort aged between 15 and 20 years. Bowlers were 1.1 times more likely to be injured for every centimetre taller and 1.1 times more likely for every kilometre per hour faster the ball was bowled.

4. Discussion

The risk of LBSI in youth fast bowlers is multi-factorial. This study is the first that has utilised multivariate analysis to quantify the relative influence of a range of routinely measured individual factors, including risk factors identified in previous research. This approach has enabled the authors to identify that the combination of younger age, a greater height and a faster bowling speed increases the risk of LBSI. Interestingly, bowling workload and technique were not significant factors in our model. The model explained approximately 36% of the variance suggesting that there are other risk factors which contribute to the development of LBSI in youth fast bowlers. This has important implications on where to best target future research and injury prevention programs.

Younger bowlers were approximately three times more likely to sustain a LBSI for each year younger within the age range 15-20 years. This finding is broadly consistent with previous research showing that bowlers under the age of 22 are particularly at risk of bone stress injury (Alway, Brooke-Wavell, et al., 2019; Blanch et al., 2015). However, other studies specifically investigating youth bowling populations have not demonstrated an age effect (Bayne et al., 2016; Kountouris et al., 2019). The current study differed from those previous with larger subject numbers and a slightly older cohort.

Taller bowlers were 1.1 times more likely to sustain a LBSI for every centimetre taller. Previous research has not found a height difference in junior bowlers with lower back injuries (not specifically LBSI) (Bayne et al., 2016; Elliott et al., 1992; Elliott, Davis, Khangure, Hardcastle, & Foster, 1993). Junior bowlers with low back injury have a higher ball release height (Foster et al., 1989), but this is influenced by other factors such as trunk lateral flexion and knee extension so it is hard to draw any conclusions with respect to height. It is possible that taller bowlers may generate greater forces in the lumbar spine due to longer lever arms which would amplify the risk of LBSI.

The increased risk with younger age and taller height may be partly attributed to a transient period of reduced bone mineral density during high linear growth (Bailey, Wedge, McCulloch, Martin, & Bernhardson, 1989; Christoffersen et al., 2016). Recent evidence has identified a bigger reduction in bone mineral density in taller males during periods of rapid growth, leaving them potentially more susceptible to fracture (Yu et al., 2019). In fact, peak lumbar spine bone mineral density is not attained until 23 years of age in males (Xue et al., 2020), with up to 10% of bone mineral content (BMC) added after linear growth has ceased (McCormack et al., 2017). It is therefore likely that the combination of being taller and younger leaves an individual at risk of a larger transient reduction in bone mineral density. Furthermore, bone architectural changes during adolescence cause a transient phase of high cortical porosity (Cheuk et al., 2018), which may leave the bone more susceptible to fracture. This may be particularly relevant to LBSI as the strength of the pars interarticularis cortical bone is considered a key factor in the ability to resist tensile and shearing forces (Cyron & Hutton, 1979).

Fast bowlers have been shown to have site-specific patterns of increased bone mass in the lumbar spine (Alway, Peirce, King, Jardine, & Brooke-Wavell, 2019), which likely gradually develops as a bowler matures. Further, during adolescence an increase in muscle strength precedes an increase in BMC by 3-6 months, consistent with the hypothesis that increased muscular load is an important driver of bone adaptation (Rauch, Bailey, Baxter-Jones, Mirwald, & Faulkner, 2004; Takei, Taketomi, Tanaka, & Torii, 2020). Collectively, the evidence suggests that younger bowlers are at increased risk of LBSI as they grow taller and become stronger, with a transient period where BMC and bone architecture adaptations lag behind increases in muscle and body weight forces. This risk decreases with age as bone matures and adapts to the forces of the fast bowling action.

Faster bowling speed was also a risk factor for the development of LBSI. This finding is intuitive given higher bowling speeds are associated with higher lumbar shear forces and more rapid development of ground reaction force (Crewe et al., 2013). Yet previous research has not reported this link (Bayne et al., 2016; Foster et al., 1989; Portus et al., 2004). This may be due to differing subject numbers, age ranges, and bowling ability between the cohorts. The current study had lower average speeds (~121 km/h) compared with the only other study to report ball speeds in junior bowlers (129 km/h) (Bayne et al., 2016) and included a wider range of bowling ability as drawn from a nation-wide testing of youth bowlers rather than a more select elite group.

Our experience with the development of youth bowlers over many years suggests that faster bowlers tend to self-select towards playing at a higher competition level given bowling faster is seen as a competitive advantage. Higher competition levels typically involve greater bowling loads. Although bowling volume was not identified as a risk factor in the current study, previous research has shown high weekly volumes to be a risk factor in the development of injury (Dennis et al., 2003) and lumbar stress fracture (Alway, Brooke-Wavell, et al., 2019) in senior bowlers. This combination of younger bowlers bowling faster, with greater bowling loads and experiencing rapid increases in strength (Rauch et al., 2004), creates a higher-risk scenario, requiring careful preparation and management to avoid LBSI as they do not have the bony maturity in their posterior-vertebral lumbar spine arches to cope with this load.

A more frequent bowling workload has been linked to injury (Dennis, Finch, & Farhart, 2005) and LBSI (Kountouris et al., 2019) in youth fast bowlers. In the current study, univariate analysis identified more frequent bowling in one, four- and 12-week intervals in the LBSI group, consistent with the previous studies. However, this was not a significant risk factor in the multivariate model. One explanation for this is the inability to pinpoint an injury date as LBSI typically develops over time (Alway, Brooke-Wavell, et al., 2019; Kountouris et al., 2019) and is only confirmed when symptoms (which in younger age groups may be poorly defined or localised (Tsukagoshi et al., 2020) or other clinical factors dictate imaging. Bowling workload may therefore have been modified in the weeks preceding diagnosis. Bone marrow oedema has also been shown to be present in approximately 40% of junior bowlers at the start of the pre-season (Kountouris et al., 2019), suggesting a lower threshold for developing clinically diagnosed LBSI which may skew bowling workload data.

Univariate analysis also identified a poorer performance of the SEBT in the LBSI group. This was consistent with previous cricket research which had shown a link between low scores on the SEBT and lower quarter injury in a group of fast bowlers (Olivier, Stewart, Olorunjub, & McKinon, 2015). The test challenges balance, strength, and mobility, making it a good composite screening tool. However, it was not a significant risk factor in the multivariate analysis suggesting other factors were more important in the development of LBSI. None of the other musculoskeletal screening measures reached statistical significance. Previous research has provided some evidence supporting the use of the prone extension test and lumbo-pelvic control test (Bayne et al., 2016) suggesting at an individual level musculoskeletal screening may still add value by identifying physical deficits and directing training programs. Physical fitness, as measured by the 2 km TT was not associated with an increased risk of LBSI. However evidence from military populations has linked poorer aerobic fitness to an increased risk of lower limb stress fractures (Rauh, Macera, Trone, Shaffer, & Brodine, 2006; Valimaki et al., 2005) and it is recommended that young fast bowlers are more likely to benefit than be hindered by higher levels of aerobic fitness.

It was also noteworthy that there was no connection identified between LBSI and bowling technique measures in the current study. Previous studies have identified greater shoulder counter-rotation (Foster et al., 1989; Portus et al., 2004) and lumbar lateral flexion (Bayne et al., 2016) as risk factors for lumbar stress fracture. The previous studies all used three-dimensional laboratory-based testing whereas the current study used a predominantly two-dimensional field-based approach. There is therefore a possibility that the reduced accuracy of the testing procedure may in part account for this discrepancy, although internal validation of the two- and three-dimensional testing methods suggest that the results are valid and inter-changeable (unpublished data). Scrutiny of the testing results showed approximately 45% (see table 2) of the non-injured bowlers had excessive shoulder counter-rotation (> 40 degrees) meaning it is very common in a junior bowling cohort and may not be a risk factor in its own right, unless combined with the other risk factors identified.

The multivariate model accounted for approximately 36% of the variance in LBSI risk, suggesting that a large proportion of the injury risk cannot be explained by age, height and bowling speed. Although age and height were identified as risk factors, rate of growth was not specifically considered. Rate of growth has been linked to an increased injury risk in junior soccer (Kemper et al., 2015) and junior athletics (Wik et al., 2020) where rapid linear growth rate and rapid skeletal maturity (assessed by X-Ray) were both risk factors for bone injury. Another possible genetically determined risk factor is intrinsic bone structure, with evidence showing a thinner pars interarticularis with less cortical bone may be more at risk of injury (Cyron & Hutton, 1979). This is consistent with more recent work showing elite military personnel with reduced tibial stiffness were 7 times more likely to suffer a stress fracture (Jepsen et al., 2013) and male runners with a stress fracture history having narrower tibias at the mid diaphysis (Popp, Frye, Stovitz, & Hughes, 2020). Future research should therefore consider incorporating measures of growth and bony architecture. Other possible risk factors include the influence of nutrition on bone health such as low energy availability, vitamin D deficiency, and calcium loss (Sale & Elliott-Sale, 2019) A further consideration for future research is to quantify all physical activity rather than just bowling volume. Together, these additional factors may contribute to the variance in LBSI risk which may help practitioners understand how a bowler exposed to similar loading as his peers may be injured when others are not.

The findings of this study should be considered in light of the following limitations. Data were collected from six different state locations in Australia over five seasons, which may have introduced variability in measurement. This was mitigated by standardised procedures and staff training. Bowling technique assessment was performed by the same national staff using the same equipment, however this assessment was not always available for the season of injury. Bowling technique appears relatively stable across spells of 10 overs (Schaefer, O'Dwyer, Ferdinands, & Edwards, 2018) and across a season (Schaefer, O'Dwyer, Ferdinands, & Edwards, 2017) but technique may change over two years with coaching intervention (Ranson, King, Burnett, Worthington, & Shine, 2009). Bowling volume was reported by bowlers and staff without objective measurement (e.g., wearable technology, video) as this was not feasible in this cohort. Additionally, bowling intensity was not recorded. Physical load from other cricket (e.g., throwing, batting) and non-cricket activities were not accounted for. Nevertheless, this study utilised routinely measured factors, and therefore provides guidance to practitioners on how to take such factors into consideration when managing young fast bowlers.

The risk of LBSI in youth fast bowlers is multi-factorial. Younger age, increased height and faster bowling speed were identified as risk factors which accounted for approximately 36% of variance between bowlers who sustained a LBSI and bowlers who did not. Practitioners should be mindful that immature vertebrae may be more susceptible to bone stress injury, and therefore assist bowlers to manage their bowling and non-bowling loads to promote positive adaptation for longevity in the sport. The relatively weak predictive model suggests that individual factors beyond the risk factors identified in this study should be considered when managing fast bowlers through adolescence.

Conflict of Interest

The authors declare no conflict of interest.

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Advancing the pro-agility test to provide better change of direction speed diagnostics

James W. D. Forster[1] *, Aaron M. Uthoff[1], Michael C. Rumpf[1], John B. Cronin[1]

[1] *School of Sport and Recreation, Auckland University of Technology, New Zealand*

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ABSTRACT

The pro-agility shuttle is commonly used by practitioners to assess change of direction (COD) performance in athletes. Total time for the test is the metric of interest; however, it provides very little insight into the accelerative, decelerative and COD ability of athletes. The aim of this study was to determine whether the utilisation of three timing lights could reliably measure different components of COD performance. The traditional pro-agility test was adapted, and additional timing lights were placed 1 m from each COD line, enabling linear acceleration, deceleration and COD performance to be isolated. Twenty-five participants (age: 18.1 ± 0.51 y, height: 177.0 ± 2.80 cm, body mass: 86.7 ± 5.45 kg) completed three sessions, consisting of three trials, separated by one week. Absolute and relative consistency was assessed using coefficients of variation (CV) and intraclass correlation coefficient (ICC), respectively. Results showed significant difference ($p < 0.05$) in the second COD between sessions two and three. Absolute consistency was considered acceptable (< 10%) for nearly all variables except Acceleration 2 and Acceleration 4 between days 2-3. Relative consistency was 'poor' to 'good' for all variables from day 1-2 (ICC = 0.13 to 0.79) and 'poor' to 'good' for days 2-3 (ICC = -0.15 to 0.86). These findings suggest that using an advanced protocol enables the distinction between different performance components of the pro-agility shuttle to be assessed with reasonable reliability.

1. Introduction

An athlete's ability to change direction is an important physical quality required in many sports. Change of direction (COD) speed tests such as the pro-agility shuttle, a foundation assessment for sports such as American football (Sierer, Battaglini, Mihalik, Shields, & Tomasini, 2008), are frequently used for both talent development and identification (Sierer et al., 2008; Vescovi & McGuigan, 2008), whereby performance can mean the difference between being selected for a team, or not (McGee & Burkett, 2003; Sierer et al., 2008). The pro-agility test, which features a total of 18.3 m (20 yards) of linear sprinting and two 180° direction changes, is commonly used due to the ease of data collection. In research and applied practice, the total time taken to complete the pro-agility shuttle has been overwhelmingly used to quantify performance (Nimphius, Geib, Spiteri, & Carlisle, 2013). However, researchers have suggested that the use of "total time" from COD and agility tests may be confounded because total time is biased to linear sprint ability (Nimphius, Callaghan, Spiteri, & Lockie, 2016). Linear sprinting and COD are considered independent athletic qualities and should be measured as such (Nimphius et al., 2013; Salaj & Markovic, 2011; Vescovi & McGuigan, 2008). Research on the pro-agility shuttle reported only 29% of total time was spent changing direction, with the rest of the time being explained by athlete linear sprint ability and physical attributes (Nimphius et al., 2013).

To provide better information to sports scientists and applied practitioners, it would be more suitable to have measures that elucidate the contribution of different performance components (i.e. acceleration, deceleration and COD), which make up total test duration, in the pro-agility shuttle. Though total time may determine selection and give a macro-appreciation of COD performance, it fails to provide an isolated measure of constituent components of acceleration, deceleration and COD ability. Therefore, knowing the contribution of constituent components will provide higher level diagnostics to better inform COD speed

*Corresponding Author: James W.D. Forster, School of Sport and Recreation, Auckland University of Technology, New Zealand, jwdfor@gmail.com

development and programming. Therefore, the aim of this study was to establish whether an advanced diagnostic protocol, with additional timing lights place 1m before each COD can be used to identify different performance components which comprise the 18.6 m of linear sprinting and two 180° COD and determine the reliability of constituent components (acceleration, deceleration and COD) within the pro-agility shuttle. We hypothesized that all constituent components would be reliable, with the linear sprinting components having the highest consistency.

2. Methods

2.1. Experimental Approach to the Problem

Twenty-five male team sport athletes performed three maximal effort attempts of the pro-agility shuttle over three testing occasions separated by seven days. In addition to timing lights at the start finish line, two additional timing gates were placed 1 m (1.1 yards) prior to each COD line. A repeated measures analysis was conducted on the raw data to determine whether between-day performance differed in terms of mean percent change, absolute consistency (CV) and relative consistency (ICC).

2.2. Participants

Twenty-five male team sport athletes (age: 18.1 ± 0.51, height: 177.0 ± 2.80 cm, body mass: 86.7 ± 5.45 kg) participated in this study. Athletes competed in various team sports, such as rugby, field hockey and soccer at high school or regional levels, had 2-3 years of strength and conditioning, and speed training experience. Participants were required to be healthy and free of injury at the time of testing. After being orally briefed on the methods and reading the information sheet, participants provided their written informed consent, or assent, prior to participating in this study and where appropriate, subjects' guardians provided written consent. Participants were notified that they were free to withdraw from the study at any point. This research was approved by the Auckland University of Technology Ethics Committee and conformed to the Declaration of Helsinki.

2.3. Procedures

Testing was conducted on an indoor rubber floor. Wearing the same clothing and footwear, athletes were required to attend four sessions: one familiarisation session where the athletes practiced performing the pro-agility shuttle and three testing sessions. Testing sessions were conducted seven days apart, at the same time of the day, under the same experimental conditions. Each testing sessions lasted approximately one hour. During each testing session, athletes performed a standardised warm up consisting of progressive sprint and COD drills interspersed with dynamic lower body stretching, followed by three pro-agility trials.

For the pro-agility run, the participants started on a centreline facing the researcher. The participants sprinted 4.57 m (5 yards) to the left, then 9.14 m (10 yards) to the right, and 4.57 m (5 yards) back to finish the test as they crossed the centreline. Three trials within each testing session were used to gather averaged performance data. Three minutes of passive rest was provided between trials to limit performance fluctuations resultant from fatigue and decrease risk of injury. The instructions provided were to, stand in a 3-point stance with their left foot 30 cm behind the start/finish line. Once the participant was stable a "go" command was given. Timing started when the turned 90 degrees to the left and ran through timing gate 1. Touched the COD line with their left hand, the participant then turned and ran to the other side and touched the COD line with their right hand, the test was then finished by turning and running back through the middle line. To ensure the athletes touched the line, the researchers observed each trial. In the case the athlete did not touch the line, slipped or had a mistrial, they were given a retrial after three minutes of passive rest.

2.4. Equipment

To quantify COD performance, timing gates (Swift Duo^{tm} timing gates, Smartspeed lite, www.fusionsport.com) were set at the start/finish line and 3.55 m (3.88 yards) either side of the start line (i.e. 1 m before each COD line) to isolate components of the COD (see Figure 1) (Sayers, 2014, 2015). Timing gate height was set at 1 m for the start/finish to correspond with approximate centre of mass and gates one meter from each COD were set at 0.75 m to account for participants lower centre of mass during the COD (Morrison, Albert, & Kuruganti, 2015; Çınarlı, Kafkas, & Kafkas, 2018). This set-up enabled total time (i.e. 18.2 m) and associated constituent components to be quantified.

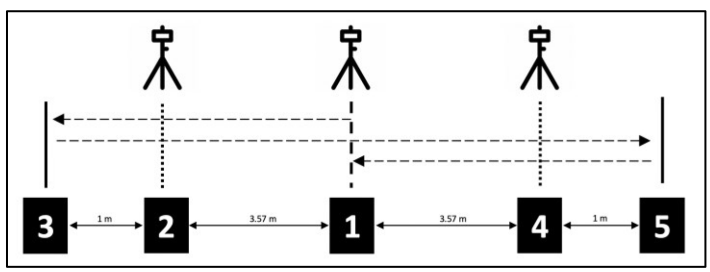

Figure 1: Advanced pro-agility diagnostic protocol

2.5. Data Analysis

Table 1 provides a description of all the variables of interest within this study. As can be observed from the table, the pro-agility test was broken into four linear accelerations and two COD components. Each of these components assessed different neuromuscular stresses often dependent on the entry velocity and therefore the decelerative-accelerative capability of the subjects.

2.6. Statistical Analysis

The two fastest trials from each session were averaged for all the variables of interest and used for subsequent analysis. Assumptions of normality and descriptive variables were tested using IBM SPSS statistical software package (version 25.0; IBM Corporation, New York, USA). Data was reported using 95% confidence limits (CL) and means. Reliability was established using pairwise analysis of averaged data of the two fastest trials. Each dependent variable was investigated between the first and second sessions and between the second and third sessions. A one-way analysis of variance (ANOVA) using repeated measures was used to determine whether between-day performance differed for total time and each of the sub-tests. To determine if systematic differences were present between testing sessions one to two and two to three, dependent *t*-tests were used. Significance was set at $p < 0.05$. Using a specifically designed spreadsheet, absolute consistency between sessions was assessed by calculating CV and mean percentage change (Hopkins, 2015). Relative consistency using test-retest correlations was measured via ICC using a two-way random model and average measures (Koo & Li, 2016). CVs of less than 10% were deemed acceptable as a percent of typical error (Uthoff, Oliver, Cronin, Winwood, & Harrison, 2018). Classification of ICC was deemed as follows: 'very poor' (< 0.20), 'poor' (0.20 - 0.49), 'moderate (0.50 – 0.74), 'good' (0.75 – 0.90) or 'excellent' (> 0.90) (Buchheit & Mendez-Villanueva, 2013). Magnitudes of change between pairwise trials were determined using Cohens *d* effect size. Effect size threshold of < 0.2, 0.2-0.6, 0.6-1.2, 1.2-2.0, and > 2.0 were determined as trivial, small, moderate, large, and extremely large (respectfully) (Cohen, 1988).

3. Results

The mean and standard deviation for each sessions' splits results are displayed in Table 2. No systematic change was observed in any measure between sessions. Mean change for all acceleration measures ranged from -2.41% to 1.90% between session 1-2 and -4.16% to 1.46% between session 2-3. Acceleration 1 showed the smallest change in mean between session 2-3 (0.02% [1.06 ± 0.09 to 1.04 ± 0.06], $d = 0.26$). Absolute consistency for accelerations

Table 1: Pro-agility diagnostic categorisation and physical assessment qualities measured

Split	Name	Explanation/Distance	Quality
1 → 2	Acceleration 1	Acceleration form the start line to first timing gate. Distance = 3.57 m (3.91 yd).	Concentric first-step quickness
2 → 3 → 2	COD 1 – lower speed entry	Timing 3.57 m (3.91 yd) entry and exit of the first COD. Distance 2.0 m (2.18 yd)	Lower intensity COD ability
2 → 1	Acceleration 2	Acceleration after the first COD from first timing gate to start/finish timing gate. Distance = 3.57 m.	Re-accelerative ability
1 → 4	Acceleration 3	Acceleration from start/finish line timing gate to entry of second COD timing gate. Distance = 3.57 m.	Re-De- accelerative ability
4 → 5 → 4	COD 2 – higher speed entry	Timing 3.57 m entry and exit of the second COD. Distance = 4.58 m.	High intensity COD ability
4 → 1	Acceleration 4	Acceleration from second timing gate to finish timing gate after the second COD. Distance = 3.57 m.	High reactive first-step quickness
1 → 3 → 5 → 1	Total time	Pro-agility total time. Distance = 18.28 m.	All the above

Note: m = metres, yd = yards, COD = change of direction measures ranged from 5.16% to 16.25% for all sessions, averaged CV for acceleration measures was 9.23% between sessions 1-2 and 10.33% between sessions 2-3. Only acceleration 1 and acceleration 3 were found to have CVs ≤ 10% between sessions 2-3. Relative consistency ranged from 'poor' to 'good' (ICC = -0.15 to 0.79) for all acceleration measures for all sessions. Only acceleration 1 and total time had an acceptable level of reliability (ICC = 0.71 [95% CL = 0.23 – 0.89], d = 0.26 and 0.86 [95% CL = 0.65 – 0.94], d = 0.09 (respectively)). Change in mean for COD measures ranged from -0.15 to 7.10% with no systematic changes observed. The smallest change in mean was observed in COD1 between session 2-3 (0.20% [0.59 ± 0.04 to 0.60 ± 0.10], d = 0.13). Absolute consistency for COD measures ranged from 5.20% to 12.77% between sessions 1-2 and 6.87% to 9.60% between session 2-3. The CVs of both COD1 and COD2 were < 10% between session 2-3. ICC ranged from 0.13 to 0.85, relative consistency much higher (> 0.60) between session 2-3. Only acceleration 1, COD 2 and total time met both reliability criteria.

Table 2: Pro-agility descriptive statistics

Split	**Mean (± SD)**			**% change of mean (95% CL)**		**CV (95% CL)**		**ICC (95% CL)**	
	Day 1	*Day2*	*Day3*	*Day1-2*	*Day2-3*	*Day1-2*	*Day2-3*	*Day1-2*	*Day2-3*
Accel 1	1.04 ± 0.06	1.06 ± 0.09	1.04 ± 0.06	0.81% (-1.67 – 3.35)	0.02% (2.74 – 2.86)	5.16% (4.15 – 6.89)	5.39% (4.28 – 7.39)	0.79 (0.49 – 0.91)	0.71 (0.23 – 0.89)
COD1	0.57 ± 0.04	0.59 ± 0.04	0.60 ± 0.10	1.40% (-1.50 – 4.34)	0.20% (-4.55 – 5.20)	5.20% (4.0 – 7.3)	9.60% (7.6 – 13.2)	0.13 (-1.1 – 0.63)	0.63 (0.06 – 0.85)
Accel 2	0.94 ± 0.10	0.93 ± 0.09	0.88 ± 0.13	-1.11% (-6.32 – 4.39)	-4.16% (-11.54 – 3.84)	11.56% 9.25 – 15.60	16.25% 12.77 – 22.69	0.41 (-0.34 – 0.74)	-0.15 (-2.19 – 0.56)
Accel 3	0.73 ± 0.06	0.71 ± 0.07	0.71 ± 0.05	-2.41% (-5.94 – 1.325)	1.46% (-2.65 – 5.74)	7.74% (6.21 – 10.38)	8.07% (6.39 – 11.12)	0.44 (-0.27 – 0.76)	0.51 (-0.15 – 0.79)
COD2	0.63 ± 0.09	0.63 ± 0.09	0.68 ± 0.11	-0.15% (-5.91 – 5.97)	7.10%* (3.38 – 10.96)	12.77% (10.21 – 17.27)	6.87% (5.45 – 9.44)	0.39 (-0.47 – 0.74)	0.85 (0.48 – 0.95)
Accel 4	0.94 ± 0.10	0.96 ± 0.12	0.91 ± 0.13	1.90% (-3.83 – 7.97)	-3.85% (-9.26 – 1.89)	12.40% (9.91 – 16.76)	11.50% (9.08 – 15.93)	0.41 (-0.44 – 0.76)	0.48 (-0.24 – 0.79)
Total Time	5.03 ± 0.28	5.04 ± 0.33	5.01 ± 0.28	-0.13% (-2.23 – 2.01)	0.63% (-0.86 – 2.15)	4.38% (3.53 – 5.85)	2.85% (2.27 – 3.89)	0.73 (0.37 – 0.89)	0.86 (0.65 – 0.94)

Note: Data are mean ± SD of each variable with the difference between sessions with the percent (%) difference given with the 95% confidence interval. * = significance level < 0.05, Accel = Acceleration, COD1 = first change of direction, COD2 = second change of direction.

4. Discussion

The pro-agility test provides a macro-understanding of change of direction ability by giving a total time. Of interest to these authors was whether the pro-agility test could be broken into sections to give a micro-understanding of the COD speed by breaking it down into smaller components provides practitioners with further insight into the COD speed strategy athletes adopt. In doing this, four acceleration measures and two CODs were identified as measures that could provide greater diagnostic information, rather than a single total time for the test. Each of these measures represented different components of COD speed as indicated in Table 1; however, prior to any use of these measures it was important to determine the reliability of the variables of interest. The main findings of this study were: 1) only acceleration 1, COD 2 and total time met the thresholds for acceptable reliability; 2) there appeared very little systematic bias between sessions 1-3, so it would seem that a familiarisation and a testing session is all that is needed to capture acceptable data.

The first measure of acceleration was the only variable that was found to have acceptable reliability. The reason for this being initiation of movement from a static position, where movement velocity would be lower than that of Acceleration 3, where assessment from a flying start may increase variability in sprint time, reducing the reliability of the measurement (Barber, Thomas, Jones, McMahon, & Comfort, 2016; Duthie, Pyne, Marsh, & Hooper, 2006; Hader, Palazzi, & Buchheit, 2015). Another reason for Acceleration 1 being the only reliable measurement of acceleration may be that acceleration was not influenced by COD, as seen in Acceleration 2 and Acceleration 4 (Barber et al., 2016; Duthie et al., 2006; Hader et al., 2015; Loturco et al., 2019) whereby, post-COD acceleration is influenced by body and force orientation (Dos'Santos, Thomas, Comfort, & Jones, 2018). These findings partially support our hypothesis that linear sprinting performance components would be reliable, yet CV > 10% for re-accelerative ability and high reactive first-step quickness indicate that the linear sprint components immediately following a COD were found to be less reliable in this study.

An interesting finding was that COD2 was the only COD measure to have acceptable reliability between sessions 2-3. This was an unexpected result because it would be assumed that the potentially higher entry velocity results in greater variability of movement, where it would be hypothesised that COD1 would have better reliability due to a lower entry velocity. It should be noted that when looking at average measures between session 2-3, COD2 took a significantly longer time to complete, than COD1 (0.65 ± 0.10 and 0.59 ± 0.06 [$p < 0.05$] (respectively)). This may be due to the increased entry velocity requiring greater braking forces during deceleration and longer ground contact time, thus impulse, when changing direction (Dos'Santos et al., 2018; Freitas et al., 2018). Similarly, (Loturco et al., 2019) further identified that those with higher acceleration had higher COD deficits, i.e. difference between linear sprint and COD. Supporting the finding by (Dos'Santos et al., 2018), that athlete ability to successfully change direction is resultant of the entry velocity and angle of directional change, where deceleration and longer ground contact times may explain the longer COD completion times when entry velocity is high. In view of this, COD measures showing acceptable CV values and 'moderate' to 'good' levels of ICC may still be used reliably (Atkinson & Nevill, 1998) for talent identification and monitoring of development. Along with this, significance reported for change of mean in the COD2 measure (7.10% [0.63 ± 0.09 to 0.68 ± 0.11]) between days 2 and 3 should be noted. The significance potentially indicates movement velocity influences COD and first-step quickness post-COD. It may be thought that reliability of the COD measures is a function of where the COD timing gates are placed, where if the gates are placed further away from the COD lines, placed equally between the start/finish and COD line, it may result in less variability. However, future research would need to be conducted to determine this. This study reported total time to be the most reliable and least variable measurement. This may be due to the amalgamation of the individual components to provide a single total time result. These findings highlight that athletes can achieve very similar total times, but the means in which they achieve these times in terms of the components of the pro-agility shuttle can differ. There was very little systematic bias between sessions 1-2, confirming there to be no predictable errors in measurement. With knowledge of this, it would seem appropriate for conduction of one testing session, with familiarisation prior, to gather acceptable performance data using this protocol.

4.1. Conclusion

To the best of the researchers' knowledge, this study is the first to advance the diagnostic value of the pro-agility test by splitting the test into a number of components. However, limitations of this study should be noted. Firstly, timing gate distance of 1 m may not be suitable when assessing taller athletes who may extend near or further than 1 m when changing direction. Additionally, timing gate height of 0.75 m may not be suitable for athletes who have an extremely low COD position. Therefore, future research is required to identify differences between timing gate set-up. Nevertheless, the results of the current research indicate that a diagnostic protocol which differentiates COD from linear sprinting and allows for assessment of performance within the pro-agility shuttle can be used to accurately identify strengths and weaknesses regarding COD and linear sprint performance.

4.2. Practical Applications

It appears that an advanced diagnostic protocol can be used to reliably distinguish between different performance components within a pro-agility shuttle. While we recommend that the linear sprinting component, high reactive COD ability, performance be interpreted with caution, the inclusion of additional timing splits provide unique information pertaining to independent physical performance capabilities. Sports scientists and strength and conditioning professionals may use this information to identify the specific performance components relevant to the sports they work with. It can be concluded the use of an advanced diagnostic testing protocol for the pro-agility shuttle, can be used to provide applied practitioners with a more isolated measure of COD ability, which is not confounded by linear sprinting, and provide specific information pertaining to areas of needed development and guide COD speed strategy.

Conflict of Interest

The authors declare no conflict of interests.

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Field-based and overspeed potentiated warm-ups increase clubhead speed and drive carry distance in skilled collegiate golfers

Alex Bliss[1*], Harrison Livingstone[1], Jamie Tallent[1],

[1]*Faculty of Sport, Allied Health and Performance Science, St Mary's University, Twickenham, London, United Kingdom*

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ABSTRACT

Warm-ups utilising post-activation performance enhancement (PAPE) strategies have been shown to increase clubhead speed (CHS) in golfers. However, the effectiveness of overspeed training using weighted clubs to elicit PAPE in CHS is unknown. The purpose of this investigation was to compare traditional, field-based warm-up activities with no potentiation activity (CON), against a field-based potentiated warm-up using high rate of force development bodyweight movements (BWP), and an overspeed warm-up using speed sticks (SSP) as the potentiation method. Thirteen skilled adult male golfers (handicap 1.0 ± 2.1) completed three testing sessions, separated by seven days. The CON, BWP and SSP warm-ups were identical, except for the potentiation method. After each warm-up condition, ten shots, separated by one minute, were recorded using a doppler radar launch monitor (Trackman 4) with CHS, ball speed (BS), carry distance (CD) and total distance (TD) recorded. A repeated measures one-way ANOVA with Bonferroni post hoc pairwise comparisons revealed increases in CHS in the BWP ($p = 0.004$) and SSP ($p = 0.003$) groups against CON, with no difference between BWP and SSP. Increased CD was observed for BWP ($p = 0.034$) and SWP ($p = 0.030$) against CON with no differences between BWP and SSP. No differences for BS or TD were observed. Warm-ups with BWP or SSP activities should be considered if players are attempting to increase CHS or CD of drives, although utilising overspeed potentiation methods appears to confer no additional benefit to bodyweight PAPE exercises in skilled collegiate golfers.

1. Introduction

Effective warm-ups for athletic performance typically follow the sequential "Raise, Activate, Mobilise, Potentiate" (RAMP) model originally proposed by Jeffreys (2007) where body temperature and heart rate are raised, muscles are activated and joints mobilised, before the musculature is primed or potentiated for the task about to be performed in a sequential manner. Golf warm-ups that contain these elements have been shown to improve determinants of drive performance in golf including clubhead speed (CHS), driving distance and strike quality (Langdown, Wells, & Graham, 2019). Conversely, warm-ups that focus on static stretching and do not adhere to the RAMP model have been demonstrated to contribute to decrements in these performance measures (Gergley, 2009). A recent review of warm-ups in golf has provided a thorough overview of the area, suggesting that to be practically viable, warm-ups should include some form of resistance exercise but with minimal equipment (Ehlert & Wilson, 2019). However, none of the studies systematically investigated contained golf-specific overspeed potentiation methods, or directly compared bodyweight resistance exercises and golf swing specific potentiation methods. The work of Tilley and McFarlane (2012) did use a weighted club, but this was used at the start of the warm-up. Overspeed potentiation methods have been shown to confer increases in swing speed in sports with a similar rotational striking movement such as baseball (Montoya, Brown, Coburn, & Zinder, 2009; DeRenne, Ho, Hetzler, & Chai, 1992). However, there is currently no evidence on overspeed potentiation methods in golf as an acute strategy to enhance CHS. Therefore, understanding whether warm-ups containing an overspeed potentiation strategy deliver maximal performance improvements is necessary.

*Corresponding Author: Alex Bliss, Department of Sport and Exercise Science, Faculty of Sport, Allied Health and Performance Science, alex.bliss@stmarys.ac.uk

Research in this area is useful as it may offer simple methods by which to increase CHS, and subsequently drive distance. Although drive distance is underpinned by a myriad of factors, the principal component for increased drive distance is increased CHS (Hume, Keogh, & Reid, 2005). For example, CHS is strongly corelated with handicap index in amateur golfers, with better players demonstrating a strong correlation with CHS (Fradkin, Sherman, & Finch, 2004). At the elite level, long-hitting golfers are more likely to score better on par four and five holes on the PGA tour (Hellstrom, Nilsson, & Isberg, 2014).

Post-activation potentiation (PAP) is a commonly used technique by strength & conditioning practitioners to acutely improve physical qualities of athletes that are required to perform forceful muscular contractions (Evetovich, Conley, & McCawley, 2015). Traditionally, PAP is observed by evoking a muscle twitch using electrical stimulation after an intense voluntary contraction, although it has also recently been defined as a voluntary force or power enhancement after a high-intensity warm-up (Blazevich & Babault, 2019). This linked, but separate phenomenon is termed the post-activation performance enhancement (PAPE) effect and is thought to result from increases in muscle temperature, muscle and muscle fibre water content, and other central and peripheral mechanisms to improve muscle activation (Blazevich & Babault, 2019). Previous studies in golf have shown that PAPE activities can elicit positive and transferable effects to golf driving performance and CHS. Research conducted by Read, Miller and Turner (2013) has shown that skilled golfers increased CHS by 2.25 miles per hour (mph) after completing a series of bodyweight countermovement jumps (CMJ). However, golfers may be reluctant to perform this type of warm-up because it is not common amongst their peers or (because it is a generic athletic movement rather than a golf movement) they may not know how to (Ehlert & Wilson, 2019). Conversely, a study of skilled golfers undergoing professional training demonstrated that warm-ups are perceived to be beneficial for golf performance, and that over 50% of players undertake air swings with a golf club as part of their preparations (Wells & Langdown, 2020). Furthermore, studies investigating changes to CHS in golf following weighted club warm-ups are lacking. Based on the research of Ehlert & Wilson (2019), this type of warm-up may be more attractive as it mimics the golf swing, but it does involve specialist equipment.

Enhancements in muscular force production from PAPE exercises have been observed following dynamic, high-speed activities (Blazevich & Babault, 2019). Studies from sports with similar rotational hitting/striking profiles to golf such as baseball have found that performing maximal effort swings as part of a warm-up with lighter than normal, or normally weighted bats can increase subsequent normal bat swing velocity by approximately 4%, but heavier bats confer no benefit (Montoya et al., 2009). Therefore, it was the purpose of this study to compare the effects of both high-rate of force development bodyweight PAPE exercise (BWP) or an overspeed warm-up using speed sticks (SSP) on golf drive performance.

2. Methods

2.1. Participants

Thirteen skilled adult male golfers (age = 20 ± 1 yrs; height= 1.82 ± 0.08 m; body mass = 77.55 ± 7.11 kg; handicap = 1.0 ± 2.1) were recruited to the study. To be included in the study, participants must have been a category one handicap (5.4 or lower) or professional. Twelve participants were amateur and one was professional, who was given a handicap of zero for the purposes of the study. Participants were recruited from a research advert which was placed at a golf college in the United Kingdom (UK) and golf clubs local to the university. All participants were free from injury. Power analysis was carried out using G*Power (v3.1.9.7) *a priori*, determining that with an estimated effect size of 0.6 (based on the similar work of Coughlan et al., (2018)) and an alpha level of 0.05. 12 participants were required to achieve a power >80%. The study was conducted in accordance with the principles of the Declaration of Helsinki (2013) and ethical approval was granted by the institution's ethics committee.

2.2. Apparatus and Task

Participants attended all testing sessions at the same time of day, separated by one-week. Participants were instructed to avoid strenuous activity 24-h prior to assessment and to arrive in a rested condition. Participants were asked to avoid eating or drinking anything other than water at least 2-h prior to assessment, and to avoid consumption of any nutritional supplements on the day of assessment. For the golf assessment, all testing sessions were carried out in an outdoor, covered driving range in the UK in similar weather conditions. A computerised launch monitor (Trackman 4, Trackman Golf, Denmark) was used to collect shot data. Participants used their own drivers, although the same balls (Srixon Range Balls, Srixon Sports Europe, UK) were used for each participant. The launch monitor was calibrated and set to a "normalised" setting for all testing sessions to account for variables such as wind direction, ground conditions, ball quality etc. Data fields recorded were: CHS, ball speed (BS), carry distance (CD) and total distance (TD). Previous research has demonstrated that the Trackman 3e (the previous model to the 4) has a median accuracy of 0.18m/s and 0.09m/s for CHS and BS respectively (Leach, Forrester, Mears, & Roberts, 2017). The Trackman 4 is a newer model than the 3e and is expected to be as accurate, if not more accurate than its predecessor (Turner, Forrester, Mears, & Roberts, 2020). If an error occurred and the launch monitor did not record all of these fields the participant was asked to re-hit.

2.3. Procedure

Participants undertook three separate protocols. Each was categorised by the type of warm-up. Each warm-up was identical in nature, except for the final activities which aimed to elicit a PAPE effect. Protocol one (CON) consisted of players completing the standardised warm-up (Table 1) with no potentiating activity and acted as a control. Protocol two added high rate of force development bodyweight plyometric exercises as a potentiating activity to the standard warm-up (BWP). Protocol three added overspeed training using Speed Sticks (SuperSpeed Golf, Tulsa, OK, USA) to the CON protocol to act as the potentiating activity (SSP). The Speed Sticks were light (20% lighter than a standard men's driver), medium (10% lighter) and heavy (around standard driver weight or up to 5% heavier). After completion of the warm-up, participants would rest for one minute before hitting 10 maximum effort drives with a 60 second rest between shots in accordance with previous research (Bliss, McCulloch, & Maxwell, 2015). Participants were asked to "swing as hard as possible, but with a technique that you would use when playing a real course".

2.4. Statistical Approach

A statistical package (IBM SPSS Statistics, v24.0, IBM Corporation, USA) was utilised for data analysis. Descriptive statistics are presented as mean ± standard deviation. The score for each dependent variable was taken as the mean value of all shots performed per condition after any outliers were removed in accordance with previous research (Bliss, McCulloch, & Maxwell, 2015) The outlier analysis employed box-and-whisker plots to remove any mishit shots. Values outside of 1.5* the lower bound for each dependent variable were removed. A one-way repeated measures analysis of variance (ANOVA) with partial eta squared (η_p^2) effect size calculations was conducted to compare means of the three groups for each dependent variable. Data were checked for sphericity using Mauchly's test, with any violations adjusted using the Greenhouse-Geiser correction. Effect sizes were classified as ≥ 0.1 = small; ≥ 0.3 = medium; ≥ 0.5 = large (Cohen, 1988). Where significant effects were observed, Bonferroni *post hoc* comparisons were used. An alpha level of ≤ 0.05 was used for significance.

Table 1: Standardised sequential RAMP-based warm-up protocol

Raise		
Skipping (2 minutes)		
Activation and mobilization		
Leg swings x 10 ES		
Resistance band shoulder external rotations 10 ES x 2		
Single leg kneeling kickbacks x 10 ES		
Lunges with rotations x 10 ES		
Overhead squats with golf club x 12		
Golf Swing Specific		
Sand wedge pitch shots x 3		
Sand wedge full shots x 3		
7 iron full shots x 2		
Driver full shots x 2		
Potentiation		
	Condition	
CON	**BWP**	**SSP**
None	CMJ 10 reps x 3	SSS Light DS x 10 reps
	Plyometric Press Ups 10 reps x 2	SSS Light NDS Side x 10 reps
		SSS Medium DS x 10 reps
		SSS Heavy DS x 10 reps

ES = Each side. CMJ= Countermovement Jump. SSS= Super Speed Stick. DS = dominant side. NDS= non-dominant side. Reps = repetitions

Table 2: Mean (± SD) values for drive variables across warm-up conditions

	CON	BWP	SSP
CHS (mph)	110.1 ± 5.5	111.6 ± 5.1*	111.6 ± 5.2*
BS (mph)	160.5 ± 8.0	161.8 ± 7.2	161.9 ± 7.9
CD (yards)	261.5 ± 16.4	267.1 ± 14.3*	268.2 ± 16.0*
TD (yards)	285.1 ± 17.8	287.7 ± 15.7	289.2 ± 18.0

*= statistically significant ($p \leq 0.05$) increase vs CON condition

3. Results

From 390 shots performed, the outlier removal process disregarded 24 shots. All participants had at least seven data points for each dependent variable for each protocol following outlier removal. Descriptive data are displayed in Table 2. ANOVA revealed significant, large effects of warm-up on CHS ($F_{(2,24)}$= 14.822, $p \leq 0.001$, $\eta_p^2 = 0.553$) and significant medium effects on CD ($F_{(2,24)}$= 5.569, $p = 0.01$, $\eta_p^2 = 0.317$). Bonferroni *post hoc* comparisons revealed, when compared to the CON condition, increased CHS in the BWP (110.1 ± 5.5 mph vs 111.6 ± 5.1 mph, $p = 0.004$, ES = 0.28) and SSP conditions (110.1 ± 5.5 mph vs 111.6 ± 5.2 mph, $p = 0.003$, ES = 0.28), but no difference between BWP and SSP ($p = 1.000$). Compared to the CON protocol, increased CD was observed for the BWP (261.5 ± 16.4 yards vs 267.1 ± 14.2 yards, $p = 0.034$. ES = 0.37) and SSP conditions (261.5 ± 16.4 yards vs 268.2 ± 16.0 yards, $p = 0.030$, ES = 0.41), but no difference between BWP and SSP ($p = 1.000$). No other significant effects were found for BS or TD (all $p > 0.05$). The dependent variables with significant effects are displayed in Figure 1.

4. Discussion

The aim of this study was to investigate three identical warm-up protocols that varied in potentiation method only and their effects on golf driving performance in skilled adult golfers. The novel element of this study is the use of overspeed training utilising weighted clubs as a potentiation method in a warm-up. The study found that utilising BWP or SSP methods can acutely increase CHS and CD in skilled golfers, but do not influence BS or TD.

Undertaking a warm-up prior to golf performance, despite recent evidence, appears to be a behaviour that is perceived as important by skilled professional golfers (Wells & Langdown, 2020) but is not well established in amateur golfers (Ehlert & Wilson, 2019). This is surprising given that much recent research has demonstrated the positive benefits of doing so (Coughlan et al., 2018; Langdown et al., 2019; Tilley & McFarlane, 2012). A key finding from this study is that undertaking maximal effort activity using BWP or SSP to finish the warm-up appears to cause a PAPE effect and creates increases in CHS and CD when compared to a warm-up with no potentiation activity. However, it also appears that there are no differences between the increase if the potentiating activity is generic (BWP) or sport-specific (SSP).

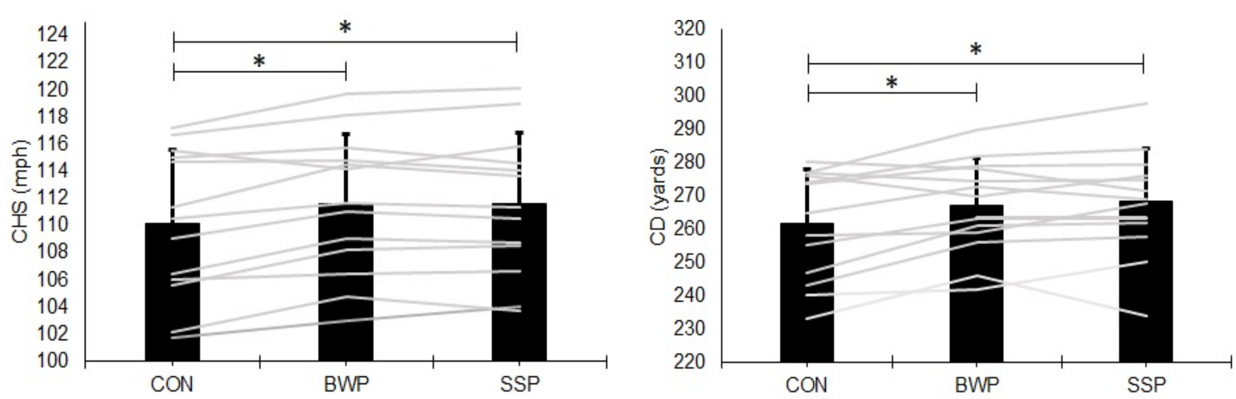

Figure 1: Mean CHS (left) and CD (right) for all warm-up conditions. Error bars represent SD. Grey lines represent individual responses. *= significant difference ($p < 0.05$)

This finding is similar to that of Langdown et al. (2019) who reported that even though both conditions were greater than the control group, there were no differences in any of the five drive metrics (BS, launch angle, total spin, dispersion, CD) monitored between their dynamic warm-up and resistance band-warm-up, with the exception of launch angle which showed a larger reduction in the dynamic group. Interestingly, while Langdown et al. (2019) did not measure CHS (they report an increase in BS), they showed no difference in CD, but increases were found in this study. This may be explained by impact conditions (spin rates, launch angles etc.) or by the high-intensity, maximal effort potentiation activities utilised in this study in comparison to the multiple repetition or duration-based dynamic and banded activities undertaken in the work of Langdown et al. (2019). To substantiate this contention, Read et al. (2013) reported an increase in CHS when using CMJs to potentiate, with their increase (2.2% equating to 2.25 mph) greater than that reported here (1.4% equating to 1.50 mph) in the BWP group. While both increases were significant, the participants in this study had higher CHS (110.1 ± 5.5 mph in the CON no potentiation condition) than those in the Read et al. study (106.9 ± 6.6 mph) (Read et al., 2013). It may be that as the participant's "normal" CHS increases, that the effect size of a BWP warm-up becomes smaller. Future research could address this by comparing warm-ups designed to elicit a PAPE effect in high and low CHS participants.

Overspeed training is a practice that has garnered attention in other rotational striking sports such as baseball (Montoya et al., 2009; DeRenne et al., 1992) but has seen a recent revival in golf, through the use of weighted golf clubs. However, despite these implements being widely used across all levels of golf including the elite level, there is currently no peer-reviewed evidence to support their use. In baseball, warm-ups utilising maximal effort wings with lightweight or normally weighted bats elicited improvements (8.3% and 4.8% increases, respectively) in bat swing speed against using heavily weighted bats (Montoya et al., 2009). In a separate warm-up study utilising a range of weighted baseball bats from very light to very heavy as potentiation methods, bats within 10% of the weight of a normal bat produced the greatest swing speeds (DeRenne et al., 1992).

A limitation of this study is that, even though the participants were accustomed to regular physical activity and we would not expect an order effect, the warm-up conditions were not randomised. Additionally, assessment of muscular recruitment pattern or activity (via electromyography) or force production (via force platform) was not conducted. Therefore, the mechanism by which the improvements in CHS and CD can only be speculatively attributed to a PAPE effect. Future research should investigate how kinetic and kinematic factors that underpin CHS or CD are enhanced as a result of a RAMP warm-up.

Although CHS and CD were enhanced in both BWP and SSP conditions, no other dependent variables demonstrated an improvement. This finding likely demonstrates that increases in CHS, while a major determinant of drive distance, is not the only factor that underpins drive performance. Launch angles (vertical and horizontal), spin rates, and centredness of strike on the clubface are also key factors that underpin early ball flight characteristics and ultimately TD (Sweeney, Mills, Alderson, & Elliot, 2013). Furthermore, Parker, Hellstrom, and Ollson (2019) demonstrated that individual swing techniques are a crucial aspect of CHS in males and females of comparable handicap and age to those in this study, although CD was less influenced by individual variance in technique. It was also suggested by that the factors that underpin CHS and CD are not transferable in males and females (Parker et al., 2019). In this regard, kinetic and kinematic variables relating to individual swing technique were not collected during the testing protocols and are limitations of this study. Further, it was conducted in a male only cohort and as such the findings should not be considered generalisable to female golfers. Future research should investigate whether there are kinetic and kinematic alterations to swing technique as a result of BWP or SSP activities in addition to monitoring drive performance.

Lastly, it is acknowledged that there were large interindividual differences in response to the BWP and SSP warm-up conditions. As an extreme example, one participant experienced a 20-yard increase in CD in the SSP condition vs CON, as where another saw a decrease of 9 yards when using a SSP warm-up versus no potentiating activity. This variation in response to warm-ups aiming to elicit a PAPE effect has been previously reported. These findings are similar to those of Langdown et al. (2019) who stated, that even though all participants in their study (and this study) were category 1, skilled players, there was considerable variability in response to warm-up conditions. Additionally, a study by Till and Cooke (2009) showed a variance of 15.3% between individual responses to PAP activities on sprint and jump performance in academy footballers. The authors stated that athletes with greater muscular strength and high training exposure had greater individual responses to PAP interventions (Till & Cooke, 2009). Furthermore, athletes with greater training experience have greater responses to PAP due to physiological make up of muscle fibres and motor units (Rixen, Lamont, & Bemben, 2007). Athletes with limited or no training experience have reduced responses to potentiating activity (Rixen et al., 2007) and lack of training experience or fitness levels is also shown to inhibit potentiating effects (Chiu, Fry, Weiss, Schilling, Brown, & Smith, 2003). Therefore, it is likely that the participant's strength characteristics will influence how they respond to RAMP based warm-ups and golfers with greater physical training experience may experience the most benefit. Limitations of this study were that strength characteristics of the participants were not measured and internal load was not monitored and therefore whether the individual responses to the BWP and SSP warm-up conditions could be attributed to strength levels is unknown. Future research in this area should collect field or laboratory measures of the participants' force generating capabilities or internal load (through heart rate or rating of perceived exertion as examples) to provide useful information that may support or help to explain the variations in drive performance between participants.

4.1. Conclusions

A warm-up that follows the RAMP protocol and contains either BWP or SSP activities elicit improvements in CHS and CD in skilled amateur male golfers. However, there were no differences between using BWP or SSP and therefore the type of potentiation activity at the end of a warm-up appears to be comparable. It is important that potentiation activities are performed at maximum effort. However, BWP and SSP warm-ups did not improve BS or TD and therefore the other kinetic and kinematic determinants of drive performance such as centredness of strike, launch angle, and spin rate need to be maintained when attempting to increase CHS and CD. Golfers can acutely increase CHS or CD through a physical warm-up if they perform BWP or SSP activities. This increase could support training or competition play and may help golfers improve their drive performance on the opening hole, which will acutely improve players' scoring potential. However, it is unknown how long these performance benefits will last and future research which studies the effects of a BWP or SSP warm-up over a longer playing duration than the opening drive is warranted.

Conflict of Interest

The authors declare no conflict of interest

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The relationship between release speed, heart rate and rate of perceived exertion across maximal and submaximal intensities in fast bowlers

Corey Perrett[1 *], Melanie Bussey[1], Peter Lamb[1]

[1]*University of Otago, School of Physical Education, Sport & Exercise Sciences, New Zealand*

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ABSTRACT

This study investigated potential internal workload measures in fast bowlers by examining the relationship between release speed, heart rate and rate of perceived exertion. It also, examined the agreement between prescribed and measured intensity in fast bowlers. Elite and provincial representative bowlers (n=8) bowled three overs each at 60%, 80% and 100% intensity and repeated this in two sessions, one week apart. Release speed was measured for each ball and rate of perceived exertion (RPE; Borg 6-20) and heart rate was measured across each over. The relationships between variables were examined using Pearson's correlations and equivalence testing. It was found that bowlers were able to scale their effort with prescribed intensities. Examining variables relative to participant maximums resulted in significant correlations between release speed, heart rate and rate of perceived exertion. Consequently, heart rate or rate of perceived exertion could be used to estimate the internal workload of fast bowlers across maximal and submaximal intensities. How these variables changed at sub-maximal intensities did not match the change in prescribed intensity, so these results should be considered in future studies and applied practice.

1. Introduction

Bowling workload has been identified as a risk factor for injury among fast bowlers (Alway, Brooke-Wavell, Langley, King, & Peirce, 2019; Hulin et al., 2013; Warren, Williams, McCaig, & Trewartha, 2018) and can be defined in terms of the external and internal load on the body. External workload, or total bowling volume (Hulin et al., 2013), is often measured as the number of balls bowled over a specified period of time, e.g., match, day, week etc. (Orchard, James, Portus, Kountouris, & Dennis, 2009; Dennis, Farhart, Goumas, & Orchard, 2003) Internal workload refers to the perceived effort or physiological demand of each ball, over or spell of bowling, in terms of the amount of stress that is placed on the internal structures of the body (Hulin et al., 2013), i.e., the greater the stress placed on the body, the higher the internal workload. Being able to effectively estimate and then monitor workload across a period of time should allow spikes in workload to be avoided, thereby reducing the risk of overuse injury in fast bowlers (Hulin et al., 2013).

How best to measure both internal and external workload (and hence estimate total workload) in fast bowlers is currently contentious. Retrospectively examining scorecards can provide an estimate of external workload during matches (Alway et al., 2019; Orchard et al., 2015; Orchard & James, 2003), while subjective recall has been used to estimate external workload during training (Bayne, Elliott, Campbell, & Alderson, 2016; Davies, Du Randt, Venter, & Stretch, 2008; Dennis et al., 2003). More recently, microsensors have also been successful at automatically detecting deliveries in a training setting (Jowitt, Durussel, Brandon, & King, 2020; McGrath, Neville, Stewart, & Cronin, 2019; McNamara, Gabbett, Chapman, Naughton, & Farhart, 2015), which has the potential to improve the measurement of external workload.

Measurement of internal workload in the literature has been reported less than external measures, with heart rate being the most common measure and rate of perceived exertion (RPE) the most common estimate (Duffield, Carney, & Karppinen, 2009; Petersen et al., 2011; Vickery, Dascombe, & Duffield, 2017). Collection of both heart rate and RPE data often appears to be

*Corresponding Author: Corey Perrett, School of Physical Education, Sport & Exercise Sciences, University of Otago, New Zealand, corey.perrett@otago.ac.nz

employed to view physiological changes that may occur over the course of a spell of bowling that could be attributed to factors such as fatigue (Burnett, Elliott, & Marshall, 1995; Duffield et al., 2009; Stretch & Lambert, 1999). However, the aforementioned measures have been used less commonly to quantify effort. The quantification methods have also differed from study to study. For example, one rating per session has been used in some instances (Hulin et al., 2013; Vickery et al., 2017), while ratings per ball bowled have been used in others (Feros, Young, & O'Brien, 2017). Since fast bowlers are unlikely to work at a consistent intensity over all deliveries in trainings, warm-ups and matches (Petersen et al., 2011), it is reasonable to expect that balls/overs will be performed at submaximal intensities, where bowlers put in less effort and/or bowl slower than they are capable of. As bowling at submaximal intensities becomes more accepted because of its potential to reduce loading (Greig & Child, 2019), there will likely be a greater amount of variability in the intensity balls are bowled at. The greater the variability, the more important an accurate internal workload estimate is, because balls bowled at different intensities will stress the body in different ways (see also, Perrett, Lamb, & Bussey, 2020). If this stress can be quantified and the internal workload estimated better, the calculation of total bowling workload could be improved, as could the quality of workload monitoring and management. Therefore, hopefully reducing the number of overuse injuries seen in fast bowlers.

The purpose of this study was to examine the relationship between release speed, the most commonly accepted intensity measure, and two potential internal workload variables, heart rate and RPE, at both maximal and submaximal intensities. Additionally, this study examined the agreement between prescribed intensity and actual intensity, according to release speed.

2. Methods

2.1. Participants

Elite level and provincial representative bowlers were sought for this study, as they were the most likely to be familiar with the variables of interest, such as prescribed effort and RPE. Eight fast bowlers participated (age: 21 ± 3 years; height: 183 ± 6 cm; weight: 82 ± 9 kg) made up of first-class (n = 2), provincial A (n = 2) and provincial u19 players (n = 4). All participants were free of lumbar stress fractures and disc herniations in the previous 12 months and provided written consent prior to data collection. All procedures were approved by the University Ethics Committee (H19/138).

2.2. Equipment and procedure

This cross-sectional study consisted of two testing sessions, one week apart, performed at an indoor cricket facility with sufficient space for all bowlers to use their full length run-up. In each session participants bowled three overs – one over each at 60%, 80% and 100% intensity; the order of the intensities was randomised prior to each session. Participants were introduced to the Borg RPE scale (6–20), and it was clarified that all ratings should be given relative to the activity of fast bowling.

Once the procedure had been explained to participants, a Polar H10 heart rate monitor (Polar Electro, Kempele, Finland) connected via Bluetooth to a smartphone containing Polar Beat (v.3.4.5), was attached and the bowler performed several practice deliveries to measure the run-up distance to be used at each intensity. Ball release speed was measured using a calibrated Stalker ATSII radar gun (Stalker Radar, TX, USA). This was held at arms-length, parallel to the ground by the experimenter who was standing 3 m behind the stumps at the bowler's end (not at the batters end (McNamara, Gabbett, Blanch, & Kelly, 2018) due to size restrictions in the facility being used). Before the commencement of the first over, baseline heart rate was recorded, and the heart rate recording started. The heart rate recording continued until the completion of the follow through of the sixth ball of that over. Upon completion of each over, participants were provided with the Borg RPE scale and asked to give a rating. Once the participants' heart rates had returned to within 10 bpm of their baseline heart rate, the protocol was repeated for the next intensity until all three overs had been completed. RPEs and heart rate was recorded for all 48 overs and release speed was recorded for all 288 balls bowled. No balls had to be repeated.

2.3. Statistical Approach

Raw heart rate data were extracted along with the release speed and RPE data into MATLAB (R2017b; The MathWorks Inc., Natick, MA) where all analyses were performed. To allow a better comparison between individuals, all variables were also calculated as a percentage of each participant's maximum value across their six overs. One-sample Kolmogorov Smirnov tests evaluated the normality of the release speed, RPE and heart rate data. Equivalence testing at the level of $\alpha = 0.05$ (i.e. 95 % equivalence testing) was used to compare measures between the two sessions, as well as to compare candidate intensity measures (RPE, heart rate) to a more common intensity measure (release speed). Although equivalence testing is relatively new to the field of biomechanics and sports science, the authors believe that it provides an improved description of the relationships between variables by testing for equivalence and rejecting the presence of the smallest effect size of interest (Lakens, Scheel, & Isager, 2018). Pearson's correlations were also calculated between release speed, heart rate and RPE to further describe the relationship between variables (reported as the Pearson correlation coefficient, 95% confidence interval and p-value). The average, absolute residuals from linear regression models were used to quantify the relationship between prescribed intensity and each of, release speed, heart rate and RPE in terms of the goodness of fit.

3. Results

One-sample Kolmogorov Smirnov tests indicate that the residuals from linear regression models fit to prescribed intensity follow a normal distribution for release speed, average and peak heart rate and RPE.

Table 1: Quantitative description of how internal workload variables changed at each of the three intensities relative to participant maximums; mean ± standard deviation (SD), inter-session equivalence ($p < 0.05$ if 90% CI is wholly contained in 95% equivalence range), slope of linear regression model fit to prescribed intensity and goodness of fit of this model (average, absolute residuals).

Variable	Intensity	Mean ± SD (%)	95% equivalence range	90% CI for difference between sessions	Change per 1% increase in prescribed intensity (%)	Average absolute residuals (%)
Average heart rate	60 %	85.0 ± 3.2 [a, b]	[-4.3, 4.3]	[-2.4, 2.6] [c]	0.15	2.26
	80%	87.9 ± 3.7 [b]	[-4.4, 4.4]	[-2.6, 6.1]		2.75
	100%	91.2 ± 3.4	[-4.5, 4.5]	[0.1, 5.9]		2.54
Peak heart rate	60 %	92.4 ± 2.8 [a, b]	[-4.6, 4.6]	[-1.6, 3.6] [c]	0.15	2.02
	80%	94.9 ± 3.5 [b]	[-4.7, 4.7]	[-1.5, 6.2]		2.53
	100%	98.5 ± 2.7	[-4.9, 4.9]	[0.7, 4.6] [c]		1.89
RPE	60 %	64.2 ± 5.6 [a, b]	[-3.1, 3.1]	[-4.1, 4.1]	0.79	4.30
	80%	79.9 ± 4.4 [b]	[-4.0, 4.0]	[-6.9, 3.5]		3.49
	100%	95.9 ± 6.1	[-4.8, 4.8]	[-8.3, 5.9]		5.15
Release speed	60 %	86.8 ± 4.0 [a, b]	[-4.3, 4.3]	[0.7, 2.6] [c]	0.25	3.26
	80%	91.6 ± 3.4 [b]	[-4.6, 4.6]	[0.4, 3.0] [c]		2.78
	100%	96.8 ± 2.1	[-4.8, 4.8]	[0.3, 1.8] [c]		1.69

[a] Significantly lower ($p < 0.05$) than 80% over
[b] Significantly lower ($p < 0.05$) than 100% overs
[c] Null hypothesis of non-equivalence between sessions is rejected

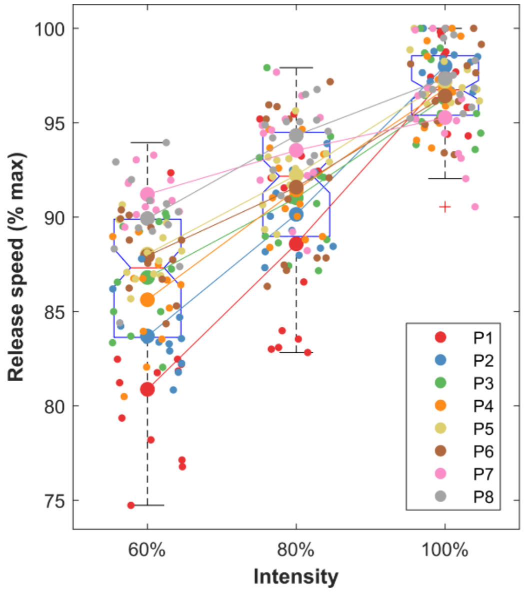
Table 1 shows that the group means of all examined variables positively scaled with intensity (60% < 80% < 100%) when examined relative to participant maximums. RPE scaled most closely (0.79% increase for every 1% increase in prescribed intensity), however the linear regression model had the worst fit at all three intensities. The model for peak heart rate fitted best in the 60% and 80% overs, while release speed fitted best in the 100% overs, and was the only variable to have inter-session equivalence at all three intensities ($p < 0.001$).

Although all participants had mean release speeds that positively scaled with intensity, there was generally an overlap between intensities when considering each ball bowled (Figure 1). Figure 1 also shows that average heart rate positively scaled with intensity in ten of the 16 individual bowling sessions, however there were some inconsistencies between intensities and sessions. For example, P3 had 80% average heart rate values that were lower than the 60% values in both sessions, and also had differences of ~10% between sessions at all intensities.

The continuous heat rate responses for each session and participant are presented in Figure 2. There are two topographical features that are similar across participants. First, the increased slope of the curve from 0-20 s and, second, the nature of the undulating shape of the curve which is apparent in all sessions and intensities for some participants (e.g., P2 and P6) and only some sessions/intensities for others (e.g., P7 and P5). It is also worth noting that the number of local maxima in the undulating curves is often only five, likely because the heart recording was stopped before the final peak.

There is a significant, moderate, positive correlation between average release speed and RPE (r (15) = 0.55 [0.32, 0.72]; $p < 0.001$). Meaning that in general, those bowling faster gave higher ratings of perceived exertion. The correlations between variables are stronger when the percentage of participants' maximum values are used. For example, between release speed and RPE (r (15) = 0.77 [0.63, 0.87]; $p < 0.001$) and between release speed and both peak (r (15) = 0.80 [0.67, 0.88]; $p < 0.001$) and average heart rate (r (15) = 0.68 [0.48, 0.81]; $p < 0.001$).

Equivalence testing with release speed as the "known criterion" measure for intensity (Dixon et al., 2018) allows a further comparison between potential intensity measures when all variables are examined relative to participant maximums. The 95% equivalence range for release speed [-4.59, 4.59] wholly contains the 90% CI for the difference between release speed and peak heart rate [-4.3, -2.8] meaning equivalence between the measures can be supported. Conversely, equivalence cannot be supported between release speed and average heart rate [2.8, 4.61] or RPE [9.2, 14.3]. However, when examined at each intensity, there is equivalence between release speed and average heart rate in the 60% overs (95% equivalence range = [-4.3, 4.3]; 90% CI = [-0.5, 3.9], $p < 0.001$) and between release speed and both RPE and peak heart rate in the 100% overs (95% equivalence range = [-4.8, 4.8]; 90% CI = [-1.6, 3.5], $p < 0.001$; [-2.4, -0.9], $p = 0.02$).



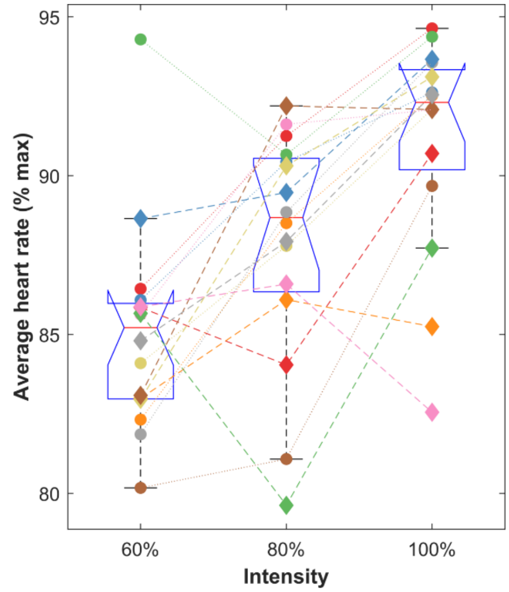


Figure 1: Boxplots showing the release speeds (left panel) and average heart rates (right panel) of all participants positively scale with prescribed intensity. For the release speed plot, large dots represent the average for each participant across both sessions; small dots represent each delivery. For the average heart rate plot, circles/dashed lines represent session one and diamonds/solid lines represent session two.

4. Discussion

Fast bowlers in this study successfully scaled their effort with the prescribed intensities, regardless of the variable used to measure 'effort'. No single effort variable provided a better measure/ estimate of release speed than another. For example, RPE values were the most similar to release speed but the linear regression model had the worst fit at all intensities. Between session differences were minimal; there was an average release speed difference of 0.75 kmh^{-1} (1.67 %) which may have resulted from the randomised order of intensities in both sessions. The relative motivation of participants may also have influenced the inter-session differences. Moreover, differing fitness levels, bowling styles, run-up lengths and physical characteristics may all have influenced the lack of strong correlations in the raw group data. The correlations between release speed and other potential intensity measures (heart rate, RPE) are stronger when examined relative to participant maximums, indicating that the normalisation of certain variables is an important consideration for model fitting.

The correlations between potential intensity variables provide some context on how the measurement of workload in fast bowlers could be improved. As mentioned by McNamara et al. (2018), release speed can be used to indicate intensity, but is not without its practical limitations that reduce its effectiveness as an intensity measure in a group training session. For example, considerable resources are required to collect release speed data from multiple bowlers working at any one time across various training nets. The moderate-strong correlation ($r = 0.55$) between release speed and RPE means that, in general, participants were able to provide an appropriate estimate of the intensity at which they were working; however, there was no equivalence with release speed in either the 60% or 80% overs. It is also not known whether the correlation between release speed and RPE would persist if specific intensities are not prescribed. There is also the consideration of when to collect the ratings – providing a rating after every ball (Feros et al., 2017) has the potential to be tedious for bowlers and practically infeasible over any period of regular training time. However, this is the only method that will exclude rest, which can affect RPE measures (Minganti et al., 2011). Conversely, session RPEs (Hulin et al., 2013; Vickery et al., 2017) assume that work rate is fairly constant, i.e. there are no spikes in effort/intensity within the session. No matter the method used, the effectiveness of RPE as a workload tool would likely improve as familiarity with the scale increases.

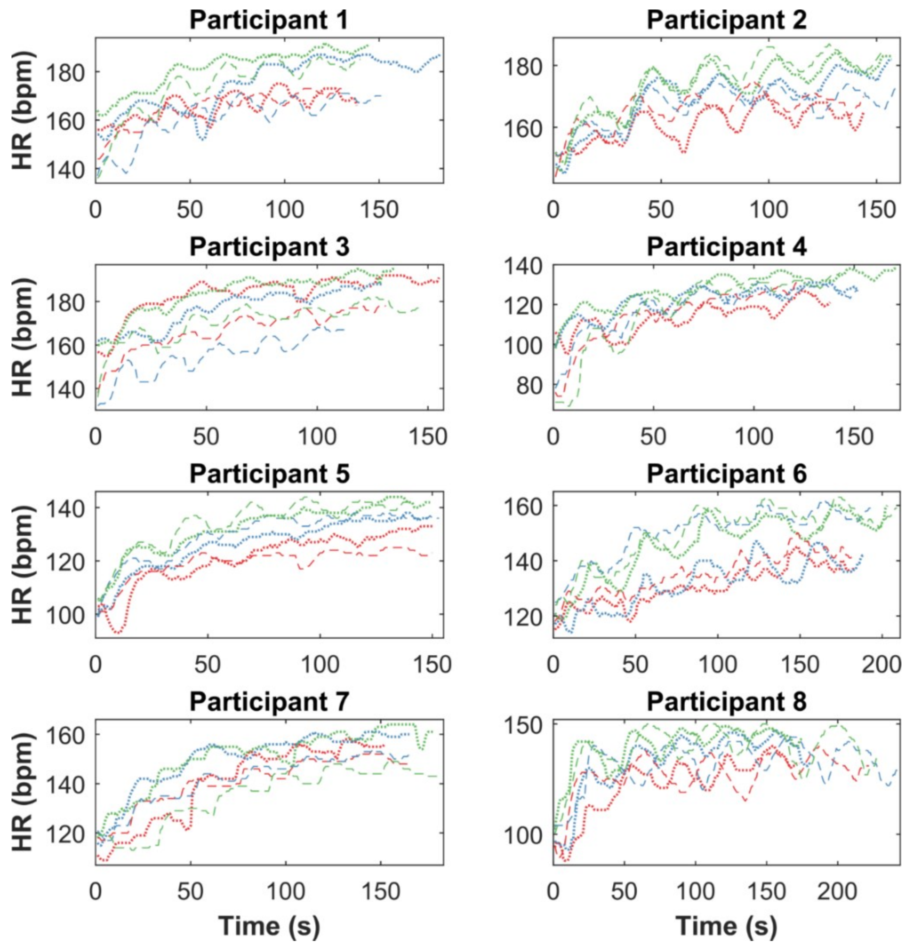


Figure 2: Heart rate responses of participants over the two sessions at each of the three intensities: 60% (red), 80% (blue) and 100% (green) in session one (dotted lines) and session two (dashed lines).

Moderate-strong correlations between release speed and both peak (r = 0.80) and average (r = 0.68) heart rate indicate that, generally, a greater amount of physiological energy/work is needed in order for bowlers to bowl faster, e.g. by increasing run-up speed (Worthington, King, & Ranson, 2013). Our results indicate that either heart rate variable may be a reasonable estimate of internal workload (as would RPE); however, further investigation regarding the specific measure used may be required before the measure could be accepted as valid and reliable. For instance, it is not clear how to deal with the heart rate responses in training, which likely include multiple bowlers, and more than one over bowled at a time, compared to a match, in which one bowler bowls one over of six consecutive deliveries at a time. Furthermore, a method to account for the inherent variability of heart rate over the course of a season (due to changing fitness levels, fatigue (Halson, 2014), temperature etc.) would need to be developed.

The relationship between prescribed and measured intensity was also of interest in this study. Although this is yet to be reported in fast bowlers, it has been reported that perceived effort (prescribed intensity) did not exactly match measured effort (throwing velocity) in baseball pitchers, with a 0.44% decrease in velocity for every 1% decrease in prescribed intensity (Melugin et al., 2019). However, this relationship assumes two things: Firstly, that that prescribed intensity will always equal the perceived effort; for athletes unfamiliar with working at submaximal intensities, this is unlikely to be the case. The second assumption is that intensity or effort can always be measured using throwing velocity/release speed. This is complicated in fast bowling given that numerous combinations of run-up length, run-up speed, effort at the crease, etc. could be combined to produce the same release speed. Additionally, the bowlers' ability to scale their bowling intensity with the prescribed intensity is complicated by the interpretation of the slope of the prescribed intensity scale: what do lower prescribed intensities such as 40%, or even 0%, correspond to? What does an RPE of 6 correspond to? Although 100% intensity can be easily determined/estimated based on release speed; comprehending submaximal intensities is more difficult and may be done inconsistently between bowlers. Regardless of these assumptions, in this study there was a 0.29%

drop in absolute release speed for every 1% decrease in prescribed intensity, similar to the relationship in baseball pitchers (Melugin et al., 2019).

Equivalence testing on fast bowling data was introduced in this study, with two potential uses analysed – comparing between two sessions (e.g. are the release speeds in session one and session two equivalent) and comparing potential intensity measures (e.g. heart rate and RPE) to more accepted measures (e.g. release speed). Although equivalence testing is relatively new to the field of biomechanics and sports science, the authors believe that it provides an improved description of the relationships between variables by testing for equivalence and rejecting the presence of the smallest effect size of interest (Lakens et al., 2018). In comparison, t-tests and ANOVA are designed to detect differences, meaning equivalence testing is more appropriate when comparing between sessions as you would expect similar results. Alternatively, using equivalence testing to compare potential measures of intensity (e.g. RPE, heart rate) to 'known' measures (Dixon et al., 2018) (e.g. release speed) provides an alternate description of the relationship between variables and provides valuable context in this study. Release speed had similar strength correlations with RPE (r = 0.77) and average heart rate (r = 0.68), but when equivalence is examined, it can be seen that average heart rate is more equivalent at submaximal intensities, whereas RPE is more equivalent at a maximal intensity. While this does not necessarily mean that heart rate is a better estimate of effort at submaximal intensities, nor likewise for RPE at a maximal intensity, it does highlight the risks of examining only a correlation coefficient. Even though RPE was more highly correlated, the RPE ratings were not equivalent to release speeds at either 60% or 80% intensity and the residuals from the RPE linear regression model were also relatively large. Describing relationships by evaluating the strength of their linearity (e.g., correlation or regression analysis), as well as by examining how similar the measures are to one another would provide more context than either one on its own, so should be given consideration in future, relevant studies.

This study was powered at 12 participants, which equates to 67% power with the sample size achieved due to the COVID-19 outbreak shortening the data collection. It is recognised that a lower statistical power is not ideal, particularly when performing correlational analyses and equivalence testing; however, the amount of release speed data collected (288 balls) was the same as two previous studies on fast bowlers (McNamara et al., 2018, 2015) Repeating the experiment with two overs at each intensity in each session and recording the heart rate for ~10 seconds longer at the end of each over would likely improve the quality of heart rate data. The same could be said for the RPE data if participants were familiarised with RPE prior to the first testing session.

5. Conclusion

The significant correlations between release speed, heart rate and RPE across submaximal intensities mean that both heart rate (peak and average) and RPE could be used to estimate internal workload in fast bowlers. Although the measures require some consideration prior to their use to maximise effectiveness, any measure that is implemented consistently will add more context to workloads than simply counting the number of balls bowled and should be encouraged. This is important for practitioners aiming to track the workload of fast bowlers in the field.

Conflict of Interest

The authors declare no conflict of interests

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Monitoring of training in high-performance athletes: What do practitioners do?

Hannah E. McGuigan[1 *], Peter Hassmén[1], Nedeljka Rosic[1, 2], Christopher J. Stevens[1]

[1]*School of Health and Human Sciences, Southern Cross University, Australia*
[2]*Marine Ecology Research Centre, Southern Cross University, Australia*

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ABSTRACT

Monitoring tools have been evaluated extensively, but it is unclear which training monitoring tools are favoured in high-performance sport settings. The primary aim of this study was therefore to describe the current practice of training monitoring used by coaches in high-performance sport settings. Secondary aims included determining (i) which monitoring tools were used with female athletes, (ii) whether these differ from those used with male athletes, and (iii) the challenges of implementing a monitoring programme. 530 national, state, and regional clubs were directly emailed and social media recruitment was also used to invite practitioners who monitored training of athletes at the pre-elite, elite, or professional level to participate in an online survey. Overall, 52 complete, and 3 partially complete responses were received. Commonly reported workload measures were training duration and training intensity that were measured every session (89% and 81%, respectively). Performance tests, measures of heart rate, and global positioning system variables were also recorded commonly (92%, 79%, and 52%, respectively). Measures of the psychological state of the athlete were used by fewer than half of the practitioners, with custom-designed wellness questionnaires focusing on fatigue, sleep quality, and general muscle soreness more common for daily use. Biochemical monitoring was reported by 25% of participants, which comprised of measures of blood lactate (88%) glucose (38%), testosterone, cortisol, and the testosterone:cortisol ratio (25% each). Of the 33 participants who identified that they monitored the training of female athletes, seven monitored hormone contraception or the menstrual phase. Monitoring performance was the most important reason for the monitoring programme; the athletes' acceptance of the monitoring programme was recognised as the greatest challenge of training monitoring. In conclusion, commonly implemented tools by practitioners were those that were easy to implement, inexpensive, and that allowed an efficient data collection and analyses over tools that may be more valid. This information is important for both sports science practitioners and researchers to continue to optimise ecologically valid training monitoring programmes and tools.

1. Introduction

Athletic training often involves periods of overloading the athlete with high volume or intensity of workload. For physiological adaptation to occur in line with the supercompensation principle, training overload must be balanced with adequate rest (Meeusen et al., 2013). When workload and recovery are not balanced, the athlete is at risk of suffering from adverse outcomes, such as prolonged fatigue, deteriorated performance, increased injury risk, overtraining syndrome, and burnout (Halson, 2014; Meeusen et al., 2013; Soligard et al., 2016). As such, monitoring an athlete and their response to training is essential to aid in training prescription and reduce the risk of these adverse outcomes (Bourdon et al., 2017).

Recently, practitioners such as sports scientists have been assigned the role of measuring the 'training load' completed by athletes (Foster, Rodriguez-Marroyo, & de Koning, 2017). The training load is defined as the work completed by the athlete and

*Corresponding Author: Hannah E. McGuigan, School of Health and Human Sciences, Southern Cross University, Australia, h.mcguigan.11@student.scu.edu.au

the associated physiological response (Akenhead & Nassis, 2016). Two different types of load have been described: external and internal (Impellizzeri, Marcora, & Coutts, 2019). The external load involves monitoring the objective measures of workload the athlete has completed during training, and may be monitored through training volume, such as the duration, intensity and the number of exercise sessions (Bourdon et al., 2017; Impellizzeri, et al., 2019). Internal load is the physiological and psychological stress imposed on the athlete in response to the training sessions. As these stressors are internal, they reflect the biochemical, physiological, psychological and anatomical aspects of the training response. The internal load may be measured using a variety of measures such as blood markers (e.g., lactate, testosterone, cortisol), heart rate indices, or mood inventories (Bourdon et al., 2017; Impellizzeri, et al., 2019). As no single marker can accurately monitor an athlete's training progress, several tools, systematically monitoring both external and internal load over long periods are recommended (Bourdon et al., 2017; Halson, 2014).

Despite considerable research into monitoring tools (Greenham, Buckley, Garrett, Eston, & Norton, 2018; Saw, Main, & Gastin, 2016), knowledge of their use by practitioners in the field is limited. McGuigan et al (2020) investigated the use of training monitoring tools and identified that tools used in the field are those that are easy to implement and use (e.g., heart rate measures, GPS data, wellness questionnaires, duration of training) compared to the more advanced monitoring tools (e.g., biochemical analysis, maximal rate of oxygen consumption). However, several gaps in the literature on the application of training monitoring provides an incomplete picture of monitoring practices. For example, self-reported wellness data have been identified as a common tool (McCall, Dupont, & Ekstrand, 2016; Starling & Lambert, 2018), but it is not often clear whether validated questionnaires or custom-designed questionnaires were used. Although measures of heart rate are also common, few studies describing applied practice report the cardiac indices being recorded (Akenhead & Nassis, 2016; Taylor, Chapman, Cronin, Newton, & Gill, 2012). The methods, timing of data collection and longitudinal consistency can also influence the effectiveness of the monitoring tools. Understanding the reasons why practitioners choose particular monitoring tools over others will provide valuable insights into the actual reasoning of training monitoring in high performance sports.

Differences in male and female physiology and biochemistry are well documented, particularly in the sport context. Men typically possess greater muscle mass and less body fat than females, contributing to greater strength, anaerobic power and aerobic power compared to their female counterparts (Sandbakk, Solli, & Holmberg, 2018). Also, female sex hormone concentrations change with the menstrual cycle and may also affect the recovery period from exercise in women (Hackney, Kallman, & Aggon, 2019). Studies on the applied practice of training monitoring have focused on male athletes (McGuigan et al., 2020), and consequently special considerations for female athletes, such as menstrual phase, have not been identified.

As such, the aim of this study was to comprehensively describe the current practice of training monitoring used by a sample of coaches in high-performance sport settings. Secondary aims included determining (i) which tools were used to monitor female athletes and whether practitioners monitor the menstrual cycle or contraceptive use, (ii) whether these tools differed to those used with male athletes, and (iii) the challenges of implementing a monitoring programme.

2. Methods

2.1. Participants

Eligible participants were practitioners monitoring the training of elite, pre-elite, or professional athletes. Athletes were defined as elite if they regularly competed at the highest national or international level of their sport; pre-elite if the athlete has the potential to reach elite status and are involved in talent development programmes; professional if they competed at the highest tier in a professional league. 530 national, state, and regional, sporting organisations and eligible participants identified from websites were emailed the survey link and asked to distribute the link within their organisation and/or complete the survey themselves. Participants were also recruited from social media and personal contacts. The study was approved by the Southern Cross University ethics committee (ECN-19-052).

2.2. Task and procedure

An online questionnaire was created using Qualtrics (2019, Utah, USA). The questionnaire items were designed and refined according to similar published articles, personal experience, and literature on training monitoring methods. The study was reviewed by the research team and a small group of external academics and coaches with specific knowledge in the area to ensure the survey had face validity and the questions were relevant to the aims of the study. The questionnaire was also piloted with ten participants with knowledge and experience in the area before further refinement. The final survey was divided into seven sections, including participant demographics, general training monitoring information, the quantification of training load, physiological monitoring, the use of validated or custom made psychological and wellness questionnaires, biochemical monitoring, and monitoring of female athletes. Each item had an 'other' option allowing participants to provide an answer that was not available. This was designed to reduce possible bias within the survey design and allow for an accurate representation of the training monitoring tools used. Participants were requested to complete the survey thinking about the training monitoring tools they have used in the past 12 months.

2.3. Statistical analysis

Frequency analysis was conducted for each item, including rank-order items and presented as frequency counts and percentages. The mean response and standard deviations are presented where applicable.

3. Results

3.1. Participant characteristics

Overall, 52 complete and 3 incomplete responses were received for monitoring of elite (n = 29; 53%), pre-elite (n = 19; 35%), or professional (n = 7; 13%) athletes. The incomplete responses were used where possible. The 55 participants in this study consisted of 45 males (81%) and 10 females (18%). Participant roles were head coach (n = 17; 31%), assistant coach (n = 5; 9%); strength and conditioning coach (n = 11; 20%); sports scientist (n = 11; 20%). Other roles included head of performance/performance manager (n = 7), sport director, head of psychological science and welfare, and physiotherapist (n = 1 each). Participants ranged in age from 22 to 69 years (*M* = 39; SD = 13) and had an average of 7.1 years (SD = 6) working with athletes at their current level. Participants monitored a range of sports including football (Australian football, rugby union, rugby league, soccer; n = 19; 35%), water sports (canoe slalom, sprint kayak, dragon boating, swimming, underwater rugby, rowing, sailing; n = 13; 24%), striking sports (cricket, hockey, squash, table tennis; n = 9; 16%), cycling and triathlon (n = 7; 13%), other (volleyball, netball, combat sports, petanque sport boules, athletics; n = 7; 13%).

3.2. General monitoring information

Participants monitored male athletes only (n = 21; 38%), female athletes only (n = 5; 9%), or both (n = 29; 53%). Participants monitored athletes in team sports (n = 15; 27%), individual sports (n = 13; 24%), or both (n = 27; 49%), and were most commonly in contact with their athletes daily (n = 18; 33%), four to six (n = 19; 35%) or two to three (n = 10; 18%) times per week. The proportion of respondents who monitored the training of only male athletes, only female athletes, or both male and female athletes for each of these measures is presented in Figure 1.

3.3. Workload monitoring

Workload monitoring was used by 54 (98%) respondents to monitor training. The frequency of use of global positioning system (GPS), session rating of perceived exertion (sRPE), and rating of perceived exertion (RPE), training duration and intensity, and workload calculations are reported in Table 1. RPE (n = 32; 73%), heart rate (n = 23; 52%), and blood lactate (n = 7; 16%) and other (e.g., athlete perception, time-based measures, power-based measured; n = 8; 18%) was used to measure training intensity. When asked what workload calculations they used, 25 (55%) respondents indicated they used acute:chronic workload ratio (n = 22; 88%), tonnage (n = 5; 19%) and training impulse (TRIMP; n = 5; 19%). Although, it was not stated which derivation of the TRIMP method was used. Participants also recorded other workload calculations (n = 9; 35%), which included: training duration multiplied by intensity based on workload training zone, monotony and strain, performance index value, principal-component analysis derived variables, 21-day rolling average, and quartiles, dive monitor (length, frequency, recovery, and underwater percentage).

GPS variables utilised by practitioners included measures of distance (n = 23; 82%), total distance covered (n = 20; 71%), speed intensity (n = 18; 64%), peak acceleration (n = 15; 54%), velocity change (n = 13; 46%), change of direction (n = 10; 36%) and other (n = 10; 36%). Respondents used an average of 5 (SD = 2; min = 2, max = 10) GPS variables for training monitoring.

3.4. Performance testing to monitor training

Physiological and performance monitoring was reported by 34 (63%) respondents to monitor training. These performance tests included sport-specific tests (n = 19; 61%), strength tests (n = 12; 39%), jump tests (n = 11; 36%), submaximal cycle test (n = 7; 23%), submaximal running test (n = 5; 16%), overground sprints (n = 4; 13%), and other tests (n = 12; 39%) including the beep test, a hybrid beep test (12.5 m surface swim and 12.5 m underwater swim), submaximal swim test, maximal oxygen consumption test, time trials, critical power test, aerobic threshold test, time to exhaustion tests across various power outputs, sport-specific training sets, aerobic and anaerobic lactic, and performance measures embedded into blocks of work.

3.5. Musculoskeletal screening

Musculoskeletal screening tests were used by 19 (56%) participants. These tests were conducted biannually (n = 6; 32%), annually (n = 4; 21%), weekly (n = 3; 16%), monthly and quarterly (n = 2, 11%, each), and daily and at other time points (n = 1; 5%). Tests included the functional movement screen (n = 12; 63%), hop test (n = 6; 32%), landing error scoring system (n = 4; 21%), star excursion balance test (n = 3; 16%), weight-bearing lunge test (n = 2; 11%), tuck jump (n = 1; 5%), and ‘other’ (n = 7; 37%).

3.6. Heart rate

The frequency of heart rate measurement collection is reported in Table 1. The types of heart rate indices used, and the timing of their collection are illustrated in Table 2.

3.7. Training diary

The frequency of the training diary reviews is reported in Table 1. The content recorded in the training diary included training type (n = 23; 100%), training duration (n = 22; 96%), sleep quality (n = 20; 87%), illness (n = 19; 83%), athlete’s mood (n = 17; 74%), supplement usage (n = 7; 30%), water intake (n = 4; 17%), and other (n = 5; 22%) including urine specific gravity, type of training, sRPE, technique and learning, readiness score, soreness, medications, appetite, fatigue, stress, worry, sleep quantity, and additional comments.

Table 1: The practitioner reported frequency of use of workload, physiological, and psychological monitoring variables

	GPS n (%)	sRPE n (%)	RPE n (%)	Training duration n (%)	Training intensity n (%)	Workload calculations n (%)	Performance tests n (%)	Heart rate n (%)	Sleep quality n (%)	Training diary n (%)	POMS n (%)	RESTQ-Sport n (%)	DALDA n (%)	Other validated questionnaires n (%)	Custom designed wellness questionnaire n (%)
Every session	20 (71)	27 (74)	26 (63)	46 (89)	36 (82)	12 (48)	1 (3)	12 (48)	-	4 (17)	1 (20)	1 (25)	-	-	3 (25)
Daily	1 (4)	1 (3)	5 (12)	1 (2)	2 (5)	4 (16)	-	-	15 (58)	4 (17)	1 (20)	1 (25)	-	2 (33)	8 (67)
4-6 times a week	2 (7)	2 (5)	3 (7)	1 (2)	2 (5)	3 (12)	-	1 (4)	4 (15)	1 (4)	-	-	-	-	1 (8)
2-3 times a week	-	2 (5)	1 (2)	1 (2)	1 (2)	2 (8)	2 (7)	2 (8)	4 (15)	5 (22)	-	-	-	-	-
Weekly	3 (11)	3 (8)	1 (2)	2 (4)	1 (2)	2 (8)	5 (17)	3 (12)	-	7 (30)	-	1 (25)	-	2 (33)	-
Fortnightly	1 (4)	-	1 (2)	-	1 (2)	-	-	1 (4)	-	-	-	-	-	-	-
Monthly	1 (4)	2 (5)	-	1 (2)	1 (2)	-	6 (20)	1 (4)	-	1 (4)	-	-	-	-	-
Quarterly	-	-	-	-	-	-	9 (30)	-	-	-	-	-	-	-	-
Biannually	-	-	-	-	-	-	3 (10)	1 (4)	-	-	-	-	-	-	-
Annually	-	-	-	-	-	-	-	-	-	-	-	1 (25)	-	1 (17)	-
Other*^	-	1 (3)	1 (2)	-	-	2 (8)	4 (13)	4 (16)	3 (12)	1 (4)	-	-	-	1 (17)	-
Total n	28	28	41	41	44	27	31[#]	25	26	23	5	4	1[#]	6	12

Note: *other time periods include during specific training blocks. GPS = global positioning system; n = number of responses; sRPE = session rating of perceived exertion; RPE = rating of perceived exertion; POMS = Profile of Mood States; RESTQ-Sport = Recovery Stress Questionnaire for Athletes; DALDA = Daily Analysis of Life Demands for Athletes. Nb: Some data for frequency of use of questionnaires are missing due to participants not completing that section of questionnaire. ^Other questionnaires including the Mental Toughness Questionnaire, the Short Recovery Stress Scale, and Total Quality Recovery. [#]Two respondents measuring heart rate and one respondent reporting performance tests and use of the DALDA did not report frequency of use.

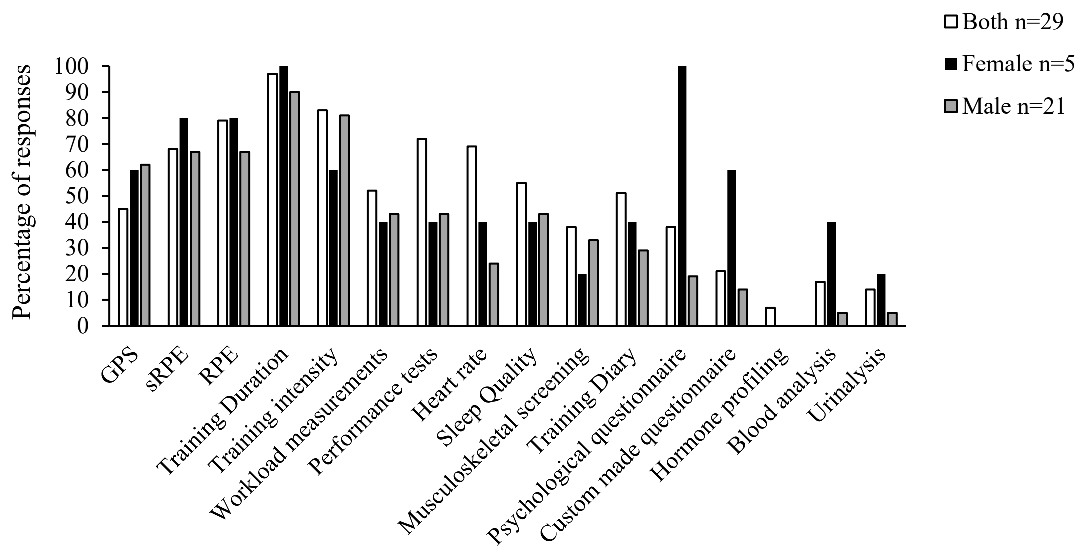

Figure 1: Percentage breakdown of monitoring tool use by respondents who monitored only male athletes, only female, or both male and female athletes

Table 2: The practitioner reported collection time of heart-rate indices

	Resting heart rate n (%)	Submaximal heart rate n (%)	Heart rate variability n (%)
After waking	6 (60)	-	5 (39)
Before exercise	3 (30)	2 (11)	4 (31)
During exercise	-	11 (61)	2 (15)
After an exercise interval	-	4 (22)	-
Immediately after exercise cessation	1(10)	-	-
15 min after exercise cessation	-	1(6)	1(8)
30 min after exercise cessation	-	-	1(8)
Total n	10	18	13

Note: n = number of responses; 'other' heart rate indices were collected before exercise, during exercise, immediately after exercise cessation, and 30 minutes after exercise cessation (n = 1; 25%, each)

Table 3: Biochemical monitoring in athletes and monitoring of female specific variables

	Hormone profiling n (%)	Blood analysis n (%)	Urinalysis n (%)	Hormone contraceptive use n (%)	Menstrual cycle phase n (%)
Daily	-	-	-	-	1 (14)
Weekly	-	1 (13)	1 (17)	2 (29)	-
Fortnightly	-	1 (13)	1 (17)	-	1 (14)
Monthly	1 (50)	-	1 (17)	1 (14)	2 (29)
Quarterly	-	3 (38)	-	-	-
Biannually	-	-	-	2 (29)	-
Annually	1 (50)	-	-	-	-
Other*	-	3 (38)	3 (50)	2 (29)	2 (29)
Total n	2	8	6	7	6^

Note: *Other collection; ^One respondent did not report frequency of use.

3.8. Psychological monitoring

Psychological monitoring was reported by 20 (36%) respondents. A total of 10 (50%) of these participants reported using validated questionnaires. The use of a custom-designed wellness questionnaire was used by 12 (22%) participants. These questionnaires comprised of between 4 and 15 questions ($M = 7$; SD=3), focussing on fatigue (n = 12; 100%), sleep quality (n = 12; 100%), general muscle soreness (n = 11; 92%), stress (n = 9; 75%), mood (n = 8; 67%), energy levels (n = 5; 42%), mental focus (n = 4; 33%), preparedness (n = 1; 8%) and ‘other’ (n = 5; 42%). Other areas include sleep quantity, new injuries, symptoms of illness, whether a medical assessment was required, and appetite. Table 1 shows the frequency of validated and custom questionnaires used.

3.9. Biochemical monitoring

Biochemical monitoring was reported by 13 (24%) respondents. The types of hormone profiling conducted by practitioners included female hormone (n = 2; 100%), male hormone (n = 2; 100%), adrenal hormone (n = 1; 50%), thyroid hormone (n = 2; 100%), and other (n = 1; 50%). Blood samples were collected via venepuncture or capillary blood sampling (n = 4; 50% each). The most commonly assessed variable was blood lactate (n = 7; 88%), followed by glucose (n = 3; 38%), and testosterone, cortisol, and the testosterone:cortisol ratio (n = 2; 25% each). Other variables (n = 4; 50%) reported include blood gas measures and haemoglobin mass. The urine sample was frequently collected first thing in the morning (n = 5; 83.3%) or after exercise (n = 1; 17%). Variables assessed included creatinine (n = 2; 33%); ketones (n = 1; 17%); glucose (n = 2; 33%); pH (n = 3; 50%), protein (n = 1; 17%); and other (urine specific gravity/ hydration levels; n = 3; 50%). Table 3 shows the frequency of assessments.

3.10. Monitoring female athlete

Thirty-three (60%) respondents who completed the survey reported monitoring either both male and female athletes or solely female athletes. Seven respondents monitored either hormone contraceptive use and/or menstrual cycle phase. The frequency of these assessments are reported in Table 3. Conditions associated with the female athlete triad were monitored by 11 (33%) of the respondents who monitored female athletes. Of these conditions, iron status and eating disorders were most commonly monitored (n = 10; 91%, for both), while bone density was not commonly monitored (n = 3; 27%).

3.11. Purpose and challenges of monitoring

Performance was the most important reason to monitor training (32%; Figure 2A). ‘Athlete buy-in’ was the major challenge to implement/maintain a monitoring programme (34%; Figure 2B.). Table 4 shows why participants did not use workload, physiological, psychological, or biochemical monitoring (Table 4).

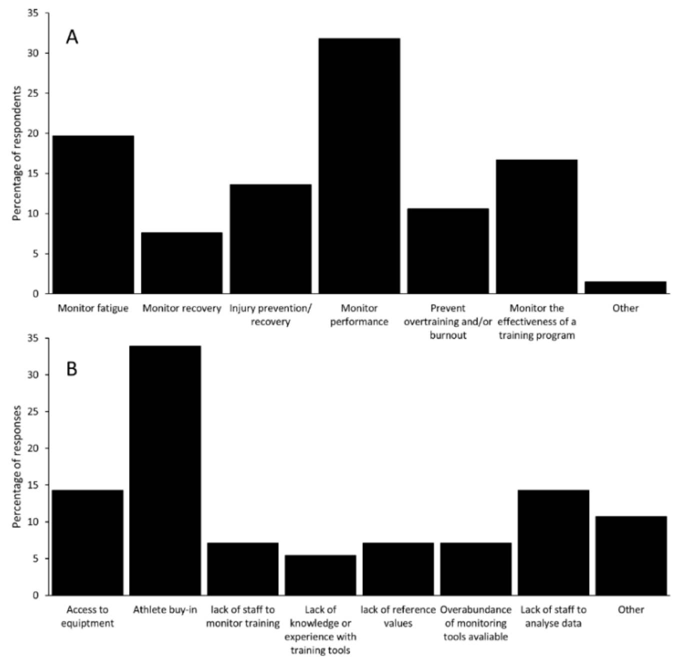

Figure 2: Key reasons to monitoring training (A) and key challenges to maintaining and/or implementing a training monitoring programme (B). *Multiple responses were allowed; some participants reported more than one key reason as the most important or challenge as the biggest barrier, therefore, Figure 2A includes 66 responses and Figure 2B includes 56 responses. The frequency of the most important factor is displayed as a percentage of respondents.

Table 4: The frequency of reasons practitioners chose not to use workload, physiological, psychological, or biochemical monitoring

	Workload	Physiological	Psychological	Biochemical
Lack of equipment	-	11 (55%)	6 (19%)	21 (53%)
Not relevant to the programme	1 (100%)	2 (10%)	3 (9%)	7 (18%)
Too time consuming	-	6 (30%)	6 (19%)	15 (38%)
Lack of staff	-	11 (55%)	10 (31%)	17 (43%)
Staff not familiar / untrained with load monitoring	-	10 (50%)	17 (53%)	16 (40%)
Results take too long to process	N/A	N/A	N/A	10 (25%)
Other	-	2 (10%)	7 (22%)	6 (15%)

4. Discussion

Monitoring the work completed by the athlete through training duration and measures of intensity were the most common ways to monitor training. Iron status and eating disorders were training monitoring considerations for female athletes. Practitioners identified that the most important reason to monitor training was to monitor performance, while the biggest challenge to monitoring was athlete 'buy-in'. These findings provide a basis for sports science researchers to optimise training monitoring programmes in the field to detect (mal)adaptation in athletes better.

4.1. Workload measures

Monitoring the work completed by the athlete was used by almost all practitioners. As the current survey investigated sports conducted both indoors and outdoors, practitioners conducting training sessions indoors would be less likely to use GPS as it is inaccurate indoors. Those who did use GPS implemented it every session, consistent with previous research (Akenhead & Nassis, 2016; Starling & Lambert, 2018; Taylor et al., 2012). Although the most commonly measured GPS variables were measures of distance, practitioners reported using an average of 5 (SD = 2.2) GPS variables to monitor load. The common parameters reported by respondents (distance, total distance covered, speed intensity, peak acceleration) are similar to the common variables reported in Akenhead and Nassis (2016). These parameters are easy to implement and interpret, indicating that practitioners may value this form of measurement.

4.2. Tools to measure performance and training response

Performance tests were reported by over half of the participants, and the current results support the previous findings of their wide use in an applied setting (Akenhead & Nassis, 2016; Starling & Lambert, 2018; Taylor et al., 2012). Commonly used performance tests (e.g., strength tests, sprints, submaximal running or cycling tests) reported in this study can be highly fatiguing. To achieve their best test performance athlete's may need to taper (Halson, 2014). Therefore, trade-off exists between the information that can potentially be gained from a performance test with the training sacrificed to taper and the fatigue subsequently experienced. This trade-off is potentially reflected by the practitioners in the current study implementing these fatiguing performance tests quarterly compared to weekly and monthly in previous research (Akenhead & Nassis, 2016; Starling & Lambert, 2018). This difference could be explained by the performance tests used, with non-fatiguing performance tests (e.g., jump tests) reported in the previous studies (Akenhead & Nassis, 2016; Starling & Lambert, 2018) compared to the more fatiguing tests (e.g., sprint tests) reported in the current study.

The use of questionnaires to monitor psychological state and wellness was low (36%). Custom-designed questionnaires were utilised as often as validated questionnaires (n=10 and n=12, respectively. This is in contrast to previous research that reported higher use of custom-designed questionnaires compared to validated questionnaires (Taylor et al., 2012). Respondents in the current study suggest that the low use of validated questionnaires may be due to a lack of education on their use (application, analysis, and results) and the time required for their implementation. Additionally, factors such as the accessibility of the measure, the time to complete, reinforcement, and social and environmental factors may influence the use of self-report measures in practice (Saw, Main, & Gastin, 2015). However, subjective monitoring is more sensitive than objective measures to both acute and chronic changes in training load (Saw et al., 2016). Therefore, the addition of a wellness questionnaire into an already established monitoring programme could be beneficial and should be implemented by to monitor the effect of training load (Saw et al., 2016).

The use of biochemical monitoring (hormone profiling, blood and urine analysis) was low. The practitioners within this study reported the main reasons they did not monitor biochemical variables was due to the lack of equipment, staff availability, knowledge and the time required to conduct the testing. This is consistent with previous literature (Taylor et al., 2012) citing the time, expenses, and knowledge of biochemical monitoring techniques being the main limitations. This study appears to be the first to investigate that markers of nutrition and metabolic health (e.g., glucose, protein, ketones), muscle status and recovery (e.g., testosterone, cortisol, testosterone: cortisol ratio), and hydration levels (e.g., urine specific gravity, pH, creatinine) are of interest to the practitioners who do monitor such biomarkers. However, biomarkers are not without their limitations. For example, the use of urine specific gravity to measure hydration status has seen inconsistent results in the literature with a delay between dehydration and rehydration impacting its applicability in acute settings (Zubac, Reale, Karnincic, Sivric, & Jelaska, 2018). Nonetheless, consistent and long-term use of selected sport and athlete-specific biomarkers are recommended to provide objective information about the health and wellbeing of the athlete (Lee et al., 2017).

4.3. Monitoring the female athlete

Few participants monitored the use of hormone contraceptives or menstrual phase. A slightly higher number monitored issues associated with the relative energy deficiency in sport (i.e., low energy availability, disordered eating, menstrual dysfunction, and low bone density). Limited research has specifically investigated the role of contraception use and menstrual cycle phase on training loads from a monitoring perspective. However, previous research in the area (e.g., menstrual phase and physical performance; Julian, Hecksteden, Fullagar, & Meyer, 2017) suggest an influence on performance and recovery. Therefore, these considerations may assist with training prescription to optimise adaptation.

The majority of respondents who indicated monitoring for the female athlete triad reported monitoring the iron levels of their female athletes. Iron deficiencies can lead to fatigue and anaemia, cognitive impairment, and immune deficiencies and have a high prevalence in athletes from a variety of sports which can impact on athletic performance (Lee et al., 2017). Therefore, it is important for practitioners to continue to monitor for iron deficiencies.

A higher percentage of respondents who monitor only female athletes reported using psychological questionnaires, including custom made questionnaires, and blood analysis compared to respondents who monitored only male athletes, or both male and female, athletes. The higher percentage of practitioners that conducted blood analysis may be due a higher risk of relative energy deficiency and lower iron levels than their male counterparts due to menstruation and therefore a greater need to monitor the status of these biochemical measures (Pedlar, Newell, & Lewis, 2019). Due to the small sample size and uneven groups this conclusion is tentative, and further research is needed to ascertain whether a difference in tool use among genders occurs to support these results.

4.4. Purpose and challenges of monitoring

The current study demonstrated that the most important reasons to monitor training for practitioners were to monitor performance, fatigue, and effectiveness of a training programme. Practitioners in previous research (Starling & Lambert, 2018; Taylor et al., 2012; Weston, 2018) have indicated that injury prevention/ reduction was the most important reason for monitoring training load and the athlete's response. This difference may be due to the previous studies investigating practitioners in team sports (Starling & Lambert, 2018; Weston, 2018), or samples consisting of majority team sports, which contrast the current sample of both individual and team sports (Taylor et al., 2012).

Athlete 'buy-in' was the biggest challenge to implementing/ maintaining a training monitoring programme. It has previously been considered a barrier to implementing and sustaining an accurate training monitoring programme (Neupert, Cotterill, & Jobson, 2019). Coaches have indicated that many athletes do not return their training data and need convincing of the benefits of providing the data (Roos, Taube, Brandt, Heyer, & Wyss, 2013). Athletes, however, reported that frequent and open feedback, and appropriate modification of training monitoring programmes as a result of the data is needed to promote adherence (Neupert et al., 2019). Coach and athlete education on training monitoring programmes may be a step forward in improving athlete buy-in.

4.5. Practical applications

The main findings of the current study were the details in the use of training monitoring tools in high-performance sport settings. This investigation has furthered previous knowledge by examining what tools are used in the field by practitioners, when they are used, and what type of information is collected. The practitioners commonly used measures of workload (training intensity and duration). Although practitioners commonly monitored their female athletes for eating disorders, less monitored the athlete's menstrual cycle. Finally, athlete buy-in was considered a challenge to the implementation and maintenance of a training monitoring programme.

Despite extensive email recruitment, only a small sample of high-performance coaches responded to the survey. As the sample is self-selecting, the results may not accurately represent the broader population. Additionally, caution should be taken when interpreting the results due to the perception of truth (consciously or subconsciously) and completeness of the answers provided. The dissemination of the results of this investigation allows practitioners to discover what their peers are using to monitor training, and how these tools are implemented (e.g., the frequency or timing), and compare to their practice and discover other monitoring strategies. Furthermore, understanding the tools that are used and valued in practice enables researchers to develop these tools and practices to be relevant and practical to coaches. Knowing what is practical and valued can help to bridge the gap between research and practice by further developing the commonly implemented tools, assessing their validity and reliability, the researcher can improve training monitoring programmes.

Conflict of Interest

The authors declare no conflict of interests.

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Rock climbers' self-reported dietary practices and supplement use in the context of supporting climbing performance

Gregory E. Peoples[1] *, Scott Parker[1], Ryan Anthony[1], Joel Craddock[2]

[1]*Centre for Medical and Exercise Physiology School of Medicine University of Wollongong, Wollongong, Australia*
[2]*Sydney School of Education and Social Work, The University of Sydney, Sydney, Australia*

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A B S T R A C T
The aim of this study was to describe the self-reported dietary practices and reported supplement use of rock climbers. A global survey was conducted (Surveymonkey™) (June–October, 2017). In total, 775 climbers completed the survey (males n = 522, females n = 251, not-identified n = 2, response-77%). This included elite (n = 56, 28 ± 8y, 65 ± 11kg), advanced (n = 449, 27 ± 7y, 67 ± 11kg) and intermediate (n = 270, 29 ± 8y, 71 ± 11kg) groups. Omnivorous diet was the most common and similar across the groups (elite 60%; advanced 56%; intermediate 61%). The prevalence rate of a vegan diet was also similar between groups (elite 7%, advanced 6%, intermediate 4%). Climbers reported (1: not important to 5: very important [mean ± SD) nutrition was most important for 'hydration' (elite 4.0±0.2, advanced 4.0 ± 0.1, intermediate 3.8 ± 0.1), 'preparation' (elite 3.5 ± 0.2, advanced 3.1 ± 0.1, intermediate 2.9 ± 0.1 $p < 0.05$) and 'recovery' (elite 3.8 ± 0.2, advanced 3.5 ± 0.1, intermediate 3.4 ± 0.1) where the prevalence of protein use for recovery was highest in elite 68% and advanced 69% compared to intermediate 55% ($p < 0.05$). Supplement intake was also equivalent between the groups (elite 1.5 ± 0.2, advanced 1.6 ± 0.1, intermediate 1.3 ± 0.1, $p > 0.05$). Caffeine was the most reported supplement used to improve performance and prevalence of consumption highest in elite climbers (elite 51%, advanced 40%, intermediate 33%, $p < 0.05$). Nitrate (<2%) and bicarbonate (<2%) were the lowest reported supplements. Climbers reported that nutrition was important to support their performance, despite a genuine lack of research in this area. Most notably, the self-reported use of nutritional supplements was low in elite and advanced climbers.

1. Introduction

Rock climbing is a sport that combines whole body strength, power, endurance and flexibility (Giles et al., 2006; Laffaye et al., 2016) underpinned by the oxygen cost of contraction (Nolan et al., 2020) and isometric fatigue of the forearm muscles (Fryer et al., 2016). Notwithstanding these attributes, the energy requirements of climbing involve both the ATP-PC and the aerobic metabolism in accordance the length of the climbing route (Watts, 2004; Billat et al., 1995). Most notably, the predictions of climbing capacity, via multifactorial analysis, is a collective grouping of these characteristics (Magiera et al., 2013; Mermier, 2000; Laffaye et al., 2016) and training prescription is one avenue for optimising climbing performance (Phillips et al., 2012).

Aside from these advances, the influence of nutrition on climbing performance is essentially unknown (Smith et al., 2017). Elite climbers have reported to use diet energy restriction, presumably with the aim of increasing power-to-weight ratio (Zapf et al., 2001). In practice, a case study of energy restriction has been reported in rock climbers on the basis of long term survival in the wilderness (Merrells et al., 2008). Furthermore, the reported prevalence of disordered eating amongst sport lead climbers has highlighted this risk is elevated in females (Michael et al., 2019). On all accounts, if energy intake over the long term fails meet energy expenditure, athlete performance can be compromised and more importantly have negative health consequences (Mountjoy et al., 2018). Most interestingly, a climber's anthropometry seems to have a minor effect on climbing performance *per se* (Laffaye et al., 2016) and as such, rock climbers may be erroneously focusing on practices such as purposeful energy or fluid restriction, carbohydrate avoidance or strict adherence to specific diets, such as veganism where there

*Corresponding Author: Gregory Peoples, School of Medicine, University of Wollongong, Wollongong, Australia, peoples@uow.edu.au

currently no evidence exists. Equally, as there is as paucity of climbing specific nutritional research, it is presently unknown what role the diet is perceived to contribute in training and competition. Therefore, the first objective of the current study was to determine the extent of dietary practices that rock climbers report to be adopting and the perceived value of this nutrition in the aim of supporting their climbing.

The physiological demands of climbing are extensively documented (Giles et al., 2006; Laffaye et al., 2016). Nutritional supplements may have some influence climbing performance, nevertheless, there is also a scarcity of research to support or reject their role in rock climbing (Smith et al., 2017). To date, the limited examples include creatine (Doran & Godfrey 2001), milk protein (Potter & Fuller 2015) and caffeine (Bellar et al., 2011; Cabañes et al., 2013) and all accounts are relatively unclear. Currently, the use of nutritional supplements is well described in other athlete populations (Erdman et al., 2006; Erdman et al., 2007) but not in rock climbers. Given that nutritional supplements should be individually prescribed and based upon sport specific evidence (Maughan et al., 2018), the second focus of the current study was to document the self-reported use of supplements used by climbers who represent the categories of elite, advance and intermeadiate climbing ability (Draper et al., 2016). Therefore, the collective aim of the current study was to i) describe and report the dietary practices and nutrition perception, as they relate to climbing performance, and ii) specifically determine which supplements are self-reported to be used by rock climbers.

2. Methods

2.1. Study design and participants

A global survey was conducted, in English, using the online tool (Surveymonkey^{TM}) during the period June–October, 2017. The constructed survey consisted of validated questions relating to rock climbing (Draper et al., 2016) and nutrition (Erdman et al., 2007) and was reviewed by the all the authors (exercise physiologist and climbing instructor [SP], dietician and outdoor instructor including climbing [JC], sports nutritionist [RA] and medical physiologist [GP]).

The survey link was distributed by social media platforms and climbing gyms. The survey link provided an electronic participant information sheet that outlined the research objectives and benefit and risks of participation. In total, 1003 participants opened the electronic information sheet containing the survey link and therefore represented the total number of participants who were invited to take part. The participants were then required to provide their informed consent and commence the survey or decline the consent and exit the survey. The study was approved by the University of Wollongong (Australia) Human Research Ethics Committee.

2.2. Self-report climbing classification

Participants reported country of residence, sex (male or female), age (years), body mass (kg), and height (m) using prescribed answers. Each participant also self-reported their primary climbing discipline (recreational or competitive and boulder, sport, lead). Participants also self-reported the number of years of climbing experienced, frequency of climbing (per week) and the average duration of climbing each session (minutes) in the last 12 months. Importantly, participants self-reported their highest climbing grade (3 successful accents) according to their country of origin and discipline. As these grades can vary according to locality, these self-reported climbing grades were all converted to the common International Rock Climbing Research Association (IRCRA) scale for classification into groups (elite through to novice) according to previously published methods (Draper et al. 2016). This conversion was completed by the two experienced climbers (SP, JC) and members of the research team and then this conversion was checked by a third team member.

2.3. Dietary behaviours and nutritional importance

Participants responded to questions that determined their self-reported dietary behaviours. This included omnivorous, ovo-lacto-vegetarian, lacto-vegetarian, ovo-vegetarian and vegan classifications. A definition of each dietary category was provided at this point of the survey. In addition, participants reported how important (1 = not important to 5 = very important) their nutrition related to the attributes of climbing performance. These included categories of preparation, recovery, hydration, body mass, delayed onset muscle soreness (DOMS), fatigue, strength, power and endurance. Finally, participants were asked if they engage in dietary behaviours such as energy intake monitoring, purposeful energy restriction, and carbohydrate loading before climbing and the intended use of carbohydrates or protein for recovery. Examples and definitions were provided for each example.

2.4. Nutritional supplements

Participants responded to a series of questions relating to use of nutritional supplements and dietary products in the last 12 months. The definition of a nutritional supplement, Dietary Supplement Health and Education Act (DSHEA) in 1994, was provided at this point of the survey. Nutritional supplements (capsules, tablets, powders or fluids), were presented with specific prompts (for example, caffeine, creatine, BCAA) specific ranging in scientific support regarding performance enhancement (Peeling et al. 2018). Participants indicated, with prescribed options, if they had used the supplement in the last 12 months for the primary purpose of supporting or enhancing climbing performance. They were also provided with opportunity to report other supplements outside of the list (free text). Dietary products were also presented with specific prompts (for example sports drinks, energy bars, gels). Participants reported if they had used each product in the last 12 months for the purpose of supporting or enhancing climbing performance.

2.5. Data analysis

All data was exported from Surveymonkey^{TM} into excel where the climbers were graded. Once this was completed the data was imported into Statistix (Version 10, Tallehassee, USA) for

Table 1: Characteristics of Elite (n = 56), Advanced (n = 449) and Intermediate (n = 270) rock climbers. Mean ± SD. *$p < 0.05$ compared to Elite group. †$p < 0.05$ compared to Advanced group.

	Elite	Advanced	Intermediate
Age (years)	28 ± 8	27 ± 7	29 ± 8
Body mass (kg)	65 ± 11	67 ± 11	71 ± 11
Height (m)	1.73 ± 0.10	1.74 ± 0.09	1.75 ± 0.09
BMI	21.5 ± 2.4	22.1 ± 2.6	22.9 ± 2.6
IRCRA scale	24 ± 2	19 ± 2*	14 ± 3*†
Climbing years	11 ± 6	8 ± 7	5 ± 5*
Sessions per week	4 ± 1	3 ± 1	3 ± 3
Time per session (min)	153 ± 64	133 ± 72	129 ± 74

analysis. One-way ANOVA was used to compare continuous variables between groups. Tukey post hoc-analysis was conducted where significant differences were returned. Categorical data was analysed using Chi-square association. Multiple comparisons for proportions were conducted where significance was returned. Alpha was set at $p < 0.05$ (80% power). Data represented as mean ± standard deviation (SD) or 95% of the confidence interval (95% CI) as appropriate.

3. Results

A total of 775 climbers provided their consent (males n = 522, females n = 251, not-identified n = 2, response rate 77%) across three significantly different IRCRA climbing groups (elite [n = 56,], advanced [n = 449] and intermediate [n = 270], $p < 0.05$) (Table 1) completed the survey. Half the climbers were residing in Australia, North America and United Kingdom and the remaining climbers were from 31 other countries across Europe, Asia and South America. There was no significant difference in age between the groups ($p > 0.05$). The elite climbers tended have a lower body mass and BMI (Table 1). Overall, primary boulder and sport disciplines of climbing were dominate across the entire sample (boulder [42%], sport [51%], traditional [7%]), although the discipline of bouldering was proportionally greater in the elite group (elite 73, advanced 48, intermediate 23%, $p < 0.05$). Elite climbers reported a significantly greater numbers of years climbing experience compared to intermediate ($p < 0.05$). Nonetheless, there was no difference in the number of sessions per week climbing ($p > 0.05$) or the time per climbing session ($p > 0.05$) (Table1).

Dietary behaviour was not different between the groups and was dominated by omnivorous category (Elite 60%, Advanced 56%, Intermediate 61%). Non-meat diets made up a smaller proportion of the sample including ovo-lacto-vegetarian (elite 7%, advanced 7%, intermediate 6%), lacto-vegetarian (elite 0, advanced 1%, intermediate 1%), pescetarian (elite 3%, advanced 6%, intermediate 3%) and vegan (elite 7%, advanced 6%, intermediate 4%) with the remaining climbers not identifying to one particular diet.

Table 2: Perceived importance (1 = not important, 5 = very important) of nutrition for supporting climbing performance by Elite (n = 56), Advanced (n = 449) and Intermediate (n = 270) rock climbers. Data presented as mean (95% CI). *$p < 0.05$ compared to Intermediate group.

	Elite	Advanced	Intermediate	*p* value
Hydration	4.0 (3.6-4.3)	4.0 (3.9-4.1)	3.8 (3.7-4.0)	0.33
Recovery	3.8 (3.4-4.1)*	3.5 (3.4-3.6)	3.4 (3.0-3.3)	0.01
Preparation	3.5 (3.2-3.9)*	3.1 (3.0-3.2)	2.9 (2.7-3.0)	0.01
Strength	3.7 (3.4-4.0)	3.6 (3.5-3.8)*	3.3 (3.1-3.5)	0.01
Power	3.6 (3.3-4.0)	3.5 (3.4-3.7)*	3.2 (3.1-3.4)	0.01
Body mass	3.6 (3.3-3.9)	3.4 (3.3-3.6)	3.4 (3.3-3.6)	0.60
Fatigue	3.3 (3.0-3.6)	3.2 (3.1-3.3)	3.0 (2.9-3.2)	0.08
Endurance	3.2 (2.9-3.5)	3.5 (3.4-3.6)	3.3 (3.1-3.4)	0.06
DOMS	3.1 (2.7-3.4)*	2.9 (2.8-3.0)	2.7 (2.5-2.8)	0.02

Elite climbers consistently ranked nutrition as 'important' across all components of preparation, recovery and fitness (Table 2). In particular, elite climbers rated a greater importance of nutrition relating to preparation, recovery and DOMS compared to intermediate climbers. Advanced climbers reported greater importance for strength and power compared to the intermediate climbers (Table 2). Notably, all three groups ranked hydration as the most important nutrition factor for supporting their climbing performance (Table 2).

Protein intake during recovery was reported by two in three elite and advanced climbers, being statistically higher in the advanced climbers compared to the intermediate (elite 68%, advanced 69%, intermediate 55%, $p < 0.05$). Only one in three climbers reported using carbohydrate loading before (elite 36%, advanced 33%, intermediate 30%) or after climbing (elite 34%, advanced 32%, intermediate 31%, $p > 0.05$) and this did not differ according to group ($p > 0.05$). Monitoring energy intake (elite 34%, advanced 27%, intermediate 24%) or restricting energy (elite 30%, advanced 24%, intermediate 22%) also did not differ between groups ($p > 0.05$).

The number of different supplements, used in the last year, was equivalent between the groups (Elite 1.5 ± 0.2, Advanced 1.6 ± 0.1, Intermediate 1.3 ± 0.1 supplements, $p > 0.05$). Of these, caffeine was the most reported supplement used to 'improve performance' (elite 51%, advanced 40%, intermediate 33%) and the proportion of elite climbers reporting its use was significantly greater than the intermediate group ($p < 0.05$) (Table 3). The least reportedly used supplements included nitrate (<2% of climbers) and bicarbonate (<2% of climbers) (Figure 2). Advanced climbers reported consuming more branch chain amino acids (BCAA) compared to intermediate climbers ($p < 0.05$) (Table 3).

The top three nutritional products used to optimise climbing performance included protein drinks, coffee, and energy / sports bars (>20%) (Table 3). Electrolyte, energy and sports drinks were the next most used products (~15% in each group) followed by liquid meals, probiotics and gels (<10%) (Figure 3). Proportionally, more elite climbers reported using a protein drink compared intermediate climbers ($p < 0.05$). Coffee was reported in 38% of elite and 33% of advanced climbers and was significantly different to the intermediate climbers (24%) ($p < 0.05$) (Table 3).

4. Discussion

There were a number of key findings from this nutritional survey of rock climbers. First, the majority of climbers, independent of climbing capability, reported following an omnivorous diet. Notwithstanding this, the proportion of climbers who reported following a diet based upon vegetarian or vegan practices was less, although there was additional evidence that energy monitoring and also energy restriction was being practiced across the groups. Second, elite and advanced climbers consistently reported that their diet was important to sustain their climbing and this included hydration, preparation and recovery, where for the later, protein was important. Third, the overall use of nutritional supplements was relatively low in elite and advanced climbers, compared to other equivalent athletes (Lun et al., 2012; Ronsen et al., 1999). Notably, caffeine was the most reported supplement used by the climbers and its proportional use was significantly higher the elite climbers compared to the intermediate cohort. The elite climbers also reported higher use of protein based drinks, and with the advanced climbers, BCAA compared to the intermediate group. In contrast, nitrates and bicarbonate, which are evidenced based sports nutritional supplements, were the lowest reportedly used.

In this study, one quarter of the climbers, independent of climbing grade, reported purposefully monitoring or restricting energy intake to optimise their performance. Intended body mass reduction is perceived as important in these athletes (Zapf et al. 2001) and disordered eating, particularly in females, has recently been reported (Joubert et al., 2020). Most interestingly, in the current study, the self-reported body mass, height and calculated BMI of elite, advanced and intermediate groups were not different and groups were equivalent to previously reported elite climbers (Michailov et al., 2009). This also supports, when body mass and height characteristics are comparable, climbing capacity is determine by trainable factors (Mermier, 2000). To date, only one case study has been published regarding energy restriction and climbing (Merrells et al., 2008) and this provided no insight regarding the interaction with climbing performance. The current study suggests that some climbers are adopting this behaviour and may risk sub-optimal energy intake. Not meeting dietary intake targets also recently been reported in a small sample size (n = 22) of adolescent climbers, with reference to fats and carbohydrates (Michael et al., 2019), although those participants were regarded as low risk for disorder eating. In the current study, this was further supported by the lower perceived value of carbohydrate loading or intake of carbohydrates during recovery, in line with a recent report in elite adult spot climbers (n = 23) who tended to avoid carbohydrates (Krzysztof & Judyta, 2019). Such approaches to nutrition, over the longer term, could indeed be compromised climbing performance and more importantly, have negative health consequences (Mountjoy et al., 2018).

High protein intake was a consistently reported in the current sample of climbers. Two thirds of the rock climbers reported consuming a whole food diet based on omnivorous definition. This focus on protein was also observed by proportionally increased consumption of BCAA in the elite and advanced climbing groups and higher reported use of protein based drinks in the elite climbers. In effect, the reliance on protein was further confirmed by two thirds of the elite and advanced climbers reporting it to be critical for optimising recovery. To date, only one study has suggested milk consumption may improve post climb recovery (Potter & Fuller, 2015) and some caution should be applied to those findings. In adolescent climbers, target protein intake has recently been described as adequate (Michael et al., 2019). In general, adequate protein provides physiological support for positive skeletal muscle adaptation and repair (Phillips, 2014). Notably, the elite climbers also rated the importance of nutrition higher than intermediate climbers for preventing DOMS. Future research should aim to detail patterns of protein consumption in elite athletes, ranging from boulders to lead climbers (Michailov et al., 2009) and with respect to their specific training and competitive requirements.

Table 3: Self-report nutritional supplement and product use (proportion of each cohort [%]), in the last 12 months, to support climbing performance in Elite (n = 56), Advanced (n = 449) and Intermediate (n = 270) rock climbers. *$p < 0.05$ versus Intermediate.

	Elite (%)	Advanced (%)	Intermediate (%)	*p* value		Elite (%)	Advanced (%)	Intermediate (%)	*p* value
Caffeine	51*	40	33	0.03	**Protein drink**	47*	37	30	0.03
Multi-vitamin	19	22	17	0.49	**Coffee**	38*	33*	24	0.01
Omega-3	10	15	16	0.49	**Energy bar**	26	26	20	0.22
Vitamin C	18	17	11	0.15	**Electrolytes**	21	17	16	0.67
BCAA	16*	16	8	0.01	**Caffeine drink**	13	13	8	0.10
Vitamin D	10	14	13	0.71	**Sports drink**	6	11	8	0.18
Calcium	12	13	10	0.38	**Liquid meals**	8	6	5	0.79
Iron	10	11	8	0.50	**Probiotics**	9	8	8	0.92
Creatine	6	10	11	0.51	**Gels**	6	4	2	0.30
Vitamin E	4	5	6	0.77					
Nitrates	2	2	2	0.89					
Bicarbonate	2	1	2	0.68					

Elimination of meat from the diet was reported by minority of the climbers. Yet, most notably, the prevalence of elite and advanced climbers that identified as vegan was higher than previously reported in other international standard athletes (Pelly & Burkhart, 2014). Notwithstanding this, there is currently no evidence that eliminating meat or animal products from the diet can improve exercise performance (Craddock et al., 2016). The current study was not able to determine if individuals also choose a vegetarian or vegan diet for ethical reasons, which could have been possible. From one perspective, a vegan diet is claimed to improve health outcomes (Appleby & Key, 2016), yet, there are also significant inadequacies reported in vegetarian and vegan populations (Craig & Mangels, 2009) and this includes long chain polyunsaturated fatty acids such as eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) (Craddock et al., 2017) which are essential for cellular function.

With this in mind, only a proportion of climbers reported to use and omega-3 fatty supplement (less than one in five) or described a diet based around fish. Low omega-3 intake is recognised globally across large proportions of the population (Stark et al., 2016). It is likely the omega-3 status in this group of climbers was also low and further studies documenting the Omega-3 Index (status) in climbers would be of value. Optimising the omega-3 status can provide direct physiological benefits, including heart and skeletal muscle function, or circulating effects such as anti-inflammation (Peoples & McLennan, 2016) and where the latter could be of value to soft tissue injury experienced by climbers (McDonald et al., 2017). In addition, climbing performance is associated with the oxygen cost of contraction and underpins contractile fatigue (Fryer et al., 2016). When DHA is optimised in the diet, skeletal muscle membranes remodel and muscle fatigue is attenuated, particularly in oxygen deprived conditions (Peoples & McLennan, 2017) and could prove to be a valuable avenue of research, particularly when the omega-3 status is likely to be low, such as climbers following a vegan diet.

The importance of hydration was obvious across all climbing grades. However, there was a low reported use of electrolyte, caffeinated or sports drinks and, although not explicitly asked, one would assume water is the obvious fluid of choice. The importance of hydration may be the due to a number of contributing factors including the warm external environment and sometimes remote locations of outdoor climbing. However, to date there are no published data to appreciate the thermoregulatory load on climbers, whether that be outdoors or indoors. Nevertheless, the current study would suggest, by self-regulation, fluid consumption is important.

The reported supplement use was low in these climbers compared to other athlete groups (Lun et al., 2012; Ronsen et al., 1999). This may due to the fact that little research has been conducted on the impact of supplements in the sport of climbing. Alternatively, other contributing factors, such athlete sponsorship, commercialisation and mainstream national programs may be influenced these behaviours.

Caffeine, a recognised ergogenic aid with evidence for performance enhancement (Peeling et al., 2018), was the most reported supplement and was proportionally higher in elite compared to intermediate climbers. Most notable, was the preference for coffee consumption rather than caffeinated drinks. Of note, only one study of caffeine ingestion and climbing performance currently exists in the literature and cannot be used to gain any insight (Cabañes et al., 2013). Caffeine is best known for improving performance across a range of physical requirements (Burke, 2008), nonetheless, it may be the physiological effects for enhancing alertness and concentration that most likely underpins its prevalent self-reported use in these climbers. Given that caffeine has a direct effect on skeletal muscle contractile recovery (Peoples & McLennan, 2017), there is a physiological basis for attenuation of contractile fatigue during gripping that could further also be explored in this population. In fact, caffeine has been demonstrated to reduce perceived pain during maximal handgrip tasks (Bellar et al., 2011). Therefore, a psychophysiological approach, in line with the mechanisms caffeine induced pain attenuation (Baratloo et al., 2016) would be of interest for future research.

Nitrate and sodium bicarbonate were the least reported supplement used by all three climbing groups. This is interesting given that both supplements have established performance enhancement effects (Peeling et al., 2018), although an interaction with climbing performance is yet to be considered. In general terms, the case of short term provision of nitrates, has been demonstrated to improve quadriceps fatigue resistance (Hoon et al., 2015). In the case of the forearm muscles, an acute dose nitrate reportedly increased the speed of the oxygen kinetics during severe intensity hand grip (Craig et al., 2018) which is highly relevant to climbing. Although not included as a supplement in the current survey, acute anthocyanin administration (via New Zealand Blackcurrant extract), sharing several common mechanistic pathways to nitrates for improved blood flow, has improved microvascular reactivity independent of brachial artery blood flow (Fryer et al., 2020b) and forearm muscle oxidative capacity (Fryer et al., 2020a) in climbers. In combination, there would seem to be an extensive opportunity to explore the role of nitrates in climbing performance.

The other notable supplements included creatine, iron, calcium and vitamin D, along with multi vitamins and vitamin C (reported to be consumed by 10-20% of the sample), although currently, there is little available research to determine if any of these are effective in regards to climbing. Creatine has a plausible basis (Peeling et al., 2018) for enhanced climbing performance, involving shorter duration and maximal power, such as bouldering and speed climbing. To date, one study has reported a short term dose of creatine in elite rock climbers improved fatigue resistance during an upper limb, non-specific wing-gate assessment (Doran & Godfrey, 2001). A further two experimental studies have indicated that creatine supplementation can improve ATP provision during a maximal handgrip task (Kurosawa et al., 2003) and time to fatigue in small muscle groups (Urbanski et al., 1999) suggesting more climbing specific research is warranted. Although on balance, there are considerations for long term use of creatine, such as increased fat free body mass (van Loon et al., 2003) and could be one explanation for the lower reporting of use by climbers in the current study.

There were limitations for this descriptive study. First, as this was an on-line international survey, all the responses were self-reported nutritional behaviours and dietary practices. It would be a great interest to further explore the diets of rock climbers using recognised tools such as the food frequency questionnaire or food records. Several other studies have already provided specific insight in cohorts of advanced climbers (n = 23) reporting suboptimal energy intake (Krzysztof & Judyta, 2019), adolescent climbers (n = 22) who in generally fail to meet daily nutritional recommendations (Michael et al., 2019) and disordered eating amongst sport lead climbers (n = 498), and most prevalent in females (Joubert et al., 2020). Second, the current responses were only interpreted based upon self-reported climbing grades. Yet, within rock climbing there are distinct disciplines including lead climbing, boulder, and speed with some reported variations in strength and body composition (Fryer et al., 2017; Michailov et al., 2009). All three disciplines were represented in this cohort and it is proposed a separate analysis, beyond the scope of this paper, would be of interest to determine the potential differences between these groups. This would also include a detailed analysis of the frequency, timing and dose of supplements used to support climbing performance through appropriate methodology such as food frequency or food records. Finally, as the survey was conducted in English, climbers from Non-English speaking nationalities were not included in the current study. This also meant that a regional comparison of the data was not possible given the bias towards English speaking climbers.

In summary, this study described the self-reported nutritional and dietary practices as well as supplement use in rock climbers, ranging from intermediate to elite (Fanchini et al., 2013; Michailov et al., 2009). Despite the scarcity of research, rock climbers recognised nutrition as important with respect their climbing performance and several anecdotal approaches to diet in the climbing community were confirmed, including an engagement in energy restriction and a focus on protein. To date, the interaction of nutrition on the demands of climbing performance has rarely been considered and future research should now focus on these interactions, using direct measures of food intake and biological assessment of nutritional status, across the climbing disciplines that differ in their physiological demands.

Conflict of Interest

The authors declare that they have no conflict of interest.

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GP conceptualised the study. GP, SP, RA, JC all contributed equally to the design of the survey. RA recruited participants and collected the data using the online tool. GP performed the data analysis. GP, SP, RA, JC all contributed to the writing of the paper. This study was not funded.

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Self-reported training variables are poor predictors of laboratory measures in cyclists

Bruna C. Mazzolani[1], Pedro Perim[1], Fabiana I. Smaira[1], Nathalia S. Rezende[1], Giulia C. Bestetti[1], Alina Dumas[1], Luana F. de Oliveira[1], Paul Swinton[2], Eimear Dolan[1], Bryan Saunders[1, 3 *]

[1]*Applied Physiology and Nutrition Research Group, School of Physical Education and Sport; Rheumatology Division; Faculdade de Medicina FMUSP, Universidade de Sao Paulo, Sao Paulo, SP, BR, University of São Paulo, Brazil*
[2]*School of Health Sciences, Robert Gordon University, Aberdeen, United Kingdom*
[3]*Institute of Orthopaedics and Traumatology, Faculty of Medicine FMUSP, University of São Paulo, Brazil*

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ABSTRACT

Cycling is an activity that depends on a range of physiological attributes, as well as genetic, dietary, lifestyle and training factors. The aim of this study was to determine what self-reported training-related factors might predict laboratory-measured physiological and performance characteristics of a heterogeneous group of male and female self-classified cyclists. Forty-eight male and fourteen female cyclists completed all aspects of the study including a training questionnaire, incremental cycling test to determine maximal oxygen uptake (VO_{2max}), 30-s Wingate test and a 4-km cycling time-trial. Principle component analysis and LASSO regression modelling were used to analyse laboratory-measures and training variables and the predictive capacity of the latter. Total distance covered across all intensities was the only training variable included in most bootstrap models (63.8%), although the actual contribution was very low with a median f^2 effect size equal to 0.01. Self-reported training variables were poor predictors of laboratory-based physiological and performance variables in this heterogeneous group of cyclists. Total distance covered was the only training variable included in most regression models, but the predictive capability of outcomes was low. Researchers and coaches should be wary that self-reported classification may not directly reflect the level of the cyclist.

1. Introduction

Endurance cycling is a predominantly aerobic activity that requires a high turnover of energy to produce mechanical power (Jeukendrup, Craig, & Hawley, 2000). Studies have demonstrated that laboratory measures such as maximal oxygen uptake (VO_{2max}), peak power output and power at the lactate or ventilatory thresholds are strong predictors of cycling performance (Bentley, McNaughton, Thompson, Vleck, & Batterham, 2001; Borszcz, Tramontin, de Souza, Carminatti, & Costa, 2018; Hawley & Noakes, 1992; Pfeiffer, Harder, Landis, Barber, & Harper, 1993). Although these laboratory variables are considered good predictors of cycling performance, less is known about the contributing factors underlying these measured variables, which are likely reflective of any number of genetic, dietary, and lifestyle influences. While these factors undoubtedly play a role, laboratory variables are also likely reflective of training habits.

Exercise intensity varies across training sessions and for convenience is often grouped into three categories, namely low intensity training (i.e., high volume, low intensity training), lactate threshold training (i.e., involves primarily continuous or intervals of moderate-intensity exercise) and high-intensity interval training (i.e., HIIT; mainly interval training, intermittent intervals, or short, high-intensity sprints) (Seiler, 2010; Stoggl & Sperlich, 2015). There is likely to be overlap in some physiological adaptations (e.g., maximal oxygen uptake [VO_{2max}], capillary density, mitochondrial biogenesis, stroke volume, etc) to these different training stimuli, but the physiological and performance adaptations that occur with HIIT are often superior to those that occur with continuous endurance training (Helgerud et al., 2007; Ni Cheilleachair, Harrison, & Warrington, 2017). Thus, the proportion of weekly training at different intensities is likely to be an important factor contributing to an individual's performance during laboratory tests, although the extent of this relationship is not well-established.

*Corresponding Author: Bryan Saunders, University of São Paulo, drbryansaunders@outlook.com

There is a large discrepancy in the scientific literature regarding how cyclists are classified (i.e., "trained", "well-trained", "professional", etc) between studies. Some authors have attempted to address this issue and provide a framework by which to classify male and female volunteers according to physiological parameters measured in the laboratory as well as weekly cycling training distances (De Pauw et al., 2013; Decroix, De Pauw, Foster, & Meeusen, 2016). However, we have previously shown that competitive (Brazilian state, national and international level) male cyclists had average VO_{2max} values of ~53 $ml \cdot kg^{-1} \cdot min^{-1}$ (Farias de Oliveira, Pires da Silva, de Salles Painelli, Gualano, & Saunders, 2016), considerably below well-trained (>60 $ml \cdot kg \cdot min^{-1}$; (Jeukendrup, Hopkins, Aragon-Vargas, & Hulston, 2008) and professional cyclists (Mujika & Padilla, 2001) despite a similar reported training volume. It is currently unknown why such large discrepancies between cycling populations exist, but it could be due to additional training factors that are not considered, such as intensity, frequency and primary mode (e.g., road or mountain bike). It would be of interest, therefore, to determine whether these self-reported training factors relate to commonly evaluated laboratory measures of cycling capacity.

Performance tests tax different energy contribution systems, with the energy supply during any given exercise protocol dependant on its intensity and duration. Maximal oxygen uptake (VO_{2max}) is the maximum capacity of an individual to transport and use oxygen during high intensity exercise (Bassett & Howley, 2000), and is one of the most frequently used physiological variables to determine aerobic power and training effects. The 30-s Wingate is a short-duration high-intensity exercise protocol predominantly supplied by anaerobic energy sources (Beneke, Pollmann, Bleif, Leithauser, & Hutler, 2002; Smith & Hill, 1991) and used to determine anaerobic performance. Middle distance time-trials (i.e., 4-km), although predominantly supplied by aerobic sources, require a substantial contribution from anaerobic sources (Craig et al., 1993) while an incremental cycling test to exhaustion is predominantly aerobic. Thus, these three protocols comprise a comprehensive battery that can determine the various physiological and performance measures essential for cycling performance, though no data exists relating training frequencies across intensity domains on these laboratory parameters.

The aim of this study was to determine whether self-reported training-related factors (e.g., intensity, frequency, supervision) might predict laboratory-measured physiological and performance characteristics of a heterogeneous group of male and female self-classified cyclists.

2. Methods

2.1. Participants

Cyclists were recruited via social media channels, with 144 cyclists (107 male, 37 female) registering initial interest. This number was further reduced to 52 male and 18 female cyclists, however, not all completed the full battery of exercise protocols due to time commitments and full exercise data is available as follows: Incremental cycling test, men = 52, women = 18; 30-s Wingate test, men = 50, women = 14; 4-km time-trial, men = 48, women = 14. Inclusion criteria included, i) aged 18-60 y; ii) minimum one-year of structured cycling training (>60 km/week (De Pauw et al., 2013). Exclusion criteria included any chronic health issue that would impede performing the exercise tests. The study was approved by the institution's Ethical Advisory Committee. Participants were informed of all protocols and risks associated with the study and provided written informed consent prior to participating.

2.2. Experimental design

The participants attended the laboratory on three separate occasions. The first visit involved anthropometric measurements and completion of the questionnaires. The next visit was for the determination of maximal cycling power output (W_{max}) and VO_{2max}; following 15 min rest, a familiarisation of the 30-s Wingate test was performed. On the last visit, participants performed the 30-s Wingate followed by a 4-km cycling time-trial (TT), separated by 20 min rest to allow recovery of muscle lactate and pH (Bangsbo, Johansen, Graham, & Saltin, 1993; Zinner et al., 2016). Participants abstained from alcohol, caffeine and strenuous exercise and completed a food record for the 24 h period prior to the initial main trial and adopted the same routine prior to the next session. Participants arrived at the laboratory a minimum of 2 h following their last food consumption.

2.3. Experimental Procedures

2.3.1. VO_{2max} test

The test was performed on a cycle ergometer (Lode Excalibur, Lode B.V., The Netherlands) and began at 100 W for men and 50 W for women, increasing 25 W every 3 min until exhaustion. Ventilatory and gas exchange measurements were recorded using a breath-by-breath system (Quark, Cosmed, Italy); the highest value averaged over 15-s was defined as VO2max. Maximal power output was calculated as the last completed stage plus the fraction of time spent in the final non-completed stage multiplied by 25 W. Outcome measures included absolute (aVO_{2max}) and relative (rVO_{2max}) VO_{2max}, absolute (aW_{max}) and relative (rW_{max}) W_{max}, and ventilatory thresholds 1 (VT1) and 2 (VT2) (Pallares, Moran-Navarro, Ortega, Fernandez-Elias, & Mora-Rodriguez, 2016).

2.3.2. 30-s Wingate

The test was performed on a cycle ergometer (Lode Excalibur, Lode B.V., The Netherlands). Following a 10-min warm-up (1.5 $W \cdot kg^{-1}$) and 1-min at 75 W, participants pedalled maximally for 30 s against a resistance of 0.7 $Nm \cdot kg^{-1}$BM for men and 0.6 $Nm \cdot kg^{-1}$BM for women. Participants could choose their preferred cadence during the warm-up but were required to maintain 60 $rev \cdot min^{-1}$ during the final 15 s prior to the Wingate to standardise the starting cadence (Kohler, Rundell, Evans, & Levine, 2010). Participants' remained seated throughout the sprint and received strong standardised verbal encouragement throughout. Data was sampled at 5 Hz. Absolute (aPPO; W) and relative (rPPO; $W \cdot kg^{-1}$) peak power output and absolute (aMPO; W) and relative (rMPO; $W \cdot kg^{-1}$) mean power output were determined.

2.3.3. 4-km cycling time-trial

The 4-km time-trial was performed on a road bicycle (Caloi, size medium) and attached to a roller connected to software (CompuTrainer, RacerMate Inc, USA), with the position of the handlebar and seat setup modified according to each participant's preference. The bicycle was calibrated (2 - 2.5 lbs resistance; chain ratio 3:1) before participants performed a 10-min warm-up at 100 W, followed by 2 min rest (on the bike). A further calibration (2.5 – 2.75 lbs; chain ratio 3:1) was performed prior to performance of the 4-km TT. Participants were instructed to complete the exercise in the fastest possible time and could change gearing throughout. Time-to-complete the time-trial (TTC; s) and mean power output (MPO; W) were recorded.

2.3.4. Questionnaires

Participants completed a training questionnaire relating to their current training routines, including information on weekly frequency (0 – 7 days) in each intensity domain (low intensity, long distance; medium distance, medium intensity; short distance, high intensity), average duration (<1 h; 1-2 h; 2-3 h; 3-4 h; 4-5 h; >5 h) of a ride in each intensity, average distance covered (<50 km; 50-100 km; 100-150 km; 150-200 km; 200-250 km; >250 km) during a ride in each intensity. Descriptors of low intensity, long distance (e.g., long duration and distance, steady pace), medium distance, medium intensity (e.g., training with intermediate sprints, escape and attacks simulations, short and active recovery intervals) and short distance, high intensity (e.g., training with many sprints, simulated starts and jumps, rest intervals) were provided and discussed with the participants to ensure understanding of the zones and accuracy of reported variables. Primary cycling mode (road cycling; mountain biking; BMX; velodrome; triathlon) and highest level of competition at which any individual was competing at (regional; state-level; national; continental/Pan-American; International/Olympic; do not compete) was extracted, as was whether the individual had a coach or not. They were also required to self-classify themselves as professional (i.e., engaged in cycling as a main paid occupation with structured training as part of a professional cycling team), amateur (i.e., engaged in cycling with structured training but not as a paid occupation but occasional to frequent involvement in competitions) or recreational (i.e., engaged in cycling without a specifically structured training program, not competing in any competitions), categories that were explained to the volunteers by an investigator. Various iterations were developed based on feedback attained during pilot testing, whereby members of the research team, and specifically those with extensive cycling experience, completed and fed-back on the questionnaire. Completion of questionnaires was performed under the supervision of an investigator who clarified any issues or confusion regarding questions.

2.3.5. Anthropometry and body composition

Measurements of weight, height and eight skinfolds (biceps, subscapular, triceps, supra spinal, abdominal, iliac crest, medial thigh and calf) were performed to estimate %body fat for men (Withers, Craig, Bourdon, & Norton, 1987) and women (Jackson & Pollock, 1985). Measurements were performed by a trained individual according to the recommendations of the International Society for the Advancement of Kinanthropometry and body composition is reported as the sum of skinfolds.

2.4. Data Analysis

Independent-samples t-tests were used to determine differences between the means of men and women for all measured continuous variables and a one-way mixed-model was used to determine differences between self-categorisation groups (recreational, amateur, professional) for men, but not women due to a lack of different groups. Welch's correction was used to account for groups heterogeneity between self-categorisation groups. To identify differences between specific groups when a significant value was shown, a Games-Howell post hoc test was performed. Statistical significance was set at $p < 0.05$.

To assess the predictive capability of training-related factors (16 variables: frequency and distance covered at low, medium and high intensity; self-reported classification; modality; coached; competition level) whilst controlling for participant demographics (5 variables: sex; age; height; weight; BMI) across a range of laboratory-measured outcomes (14 variables), a multivariable method was required that avoided problems with overfitting. Therefore, LASSO (least absolute shrinkage and selection operator) regression models were conducted as a penalised regression method. Models were generated using the glmnet package (Friedman, Hastie, & Tibshirani, 2010) in R with statistical properties of estimates based on 10,000 bootstrap samples.

To summarise the predictive capability of training-related factors, a collective laboratory-based measure representing "average" performance across tests was created. The dependent variable was achieved by conducting a principal component analysis (PCA) and using the weights obtained from the first principal component. PCA was conducted with imputation of missing data using the imputePCA function from the missMDA package in R (Josse & Husson, 2016). LASSO regression was then conducted with model inputs and the PCA derived measure. Importance of model inputs were described by the percentage inclusion in models, the size of the regression coefficient and Cohen's f^2 effect size which was calculated using standard formula (Cohen, 1988). Outcomes are reported as mean ± 1SD unless otherwise stated.

3. Results

3.1. Demographic, training, physiological and performance characteristics

The sample consisted of five professional male cyclists, 45 men and 16 women self-reported as amateur while the remaining two men and one woman considered themselves recreational. One woman did not classify herself in any category. According to VO_{2max} classifications (De Pauw et al., 2013; Decroix et al., 2016), twelve men and four women were classified as untrained, 24 men and ten women as recreationally trained, 15 men and three women as trained and one man and one woman as well-trained (Figure 1). The primary cycling modes of the sample of cyclists consisted of road cycling (N = 42), mountain biking (N = 21) and triathlon (N = 6); one individual did not choose a primary modality. Twenty-one men and eight women were supervised by a coach.

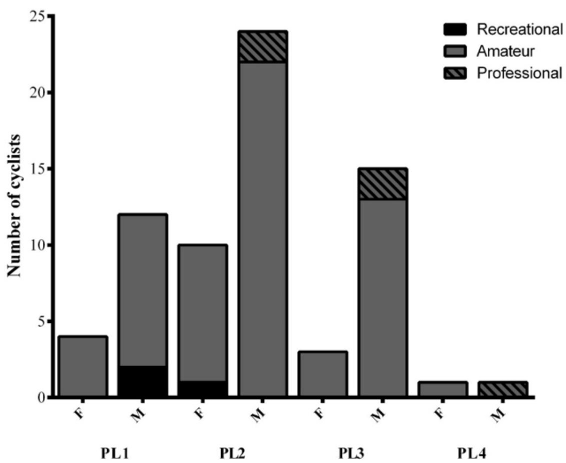

Figure 1: Number of cyclists in each category according to recommendations (De Pauw et al., 2013; Decroix et al., 2016) (x-axis) and self-reported classification (within columns). F = Female, M = Male, PL1 = untrained, PL2 = active (Females) or recreationally trained (Males), PL3 = trained, PL4 = well-trained. Twelve men and 4 women were classified as untrained (PL1), 24 men and 10 women as recreationally trained (PL2), 15 men and 3 women as trained (PL3) and 1 man and 1 woman as well-trained (PL4). Five men self-reported as professional cyclists, 45 men and 16 women self-reported as amateur while the remaining 2 men and 1 woman considered themselves recreational. One woman didn't classify herself in any category.

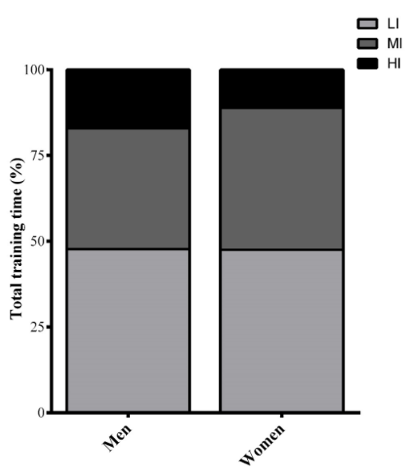

Figure 2: Relative training distribution across low (LI), medium (MI) and high (HI) intensity zones in men and women as a percentage of total weekly training volume.

All laboratory measured variables showed a sex difference (all $p \leq 0.05$), except relative power output at the ventilatory thresholds. Weight, aVO_{2max}, rVO_{2max}, VT2 W_{max}, weekly training distance covered, and duration was different between men's self-classification groups (all $p < 0.05$), with greater values in professionals > amateur > recreational (Table 1). Similarly, rPPO, aMPO and rMPO were greater for professionals compared to the recreational group (all $p < 0.01$) (Table 1). rW_{max} was different between recreational and professional groups with greater values for professional, with no differences between amateur and recreational or professional and amateur. Average weekly distance and training duration across all intensities was 307 ± 140 km and 10.3 ± 3.6 hours for men, 278 ± 107 km and 8.8 ± 4.5 hours for women. The distribution per training intensity was as follows: Low intensity: 47.7% (Men: 47.7%; Women: 47.5%); Moderate intensity: 36.7% (Men: 35.2%; Women: 41.4%) and High intensity: 15.7% (Men: 17.1%; Women: 11.1%) (Figure 2).

3.2. LASSO Regression

The importance of each predictor was initially assessed by quantifying percentage inclusion in LASSO bootstrap samples across the laboratory-based measurements (Figure 3). The median value was largest for sex (98.8%), followed by weekly cycling distance across all intensities (63.8%) and age (57.0%). In general, the remaining predictor variables did not feature frequently in LASSO models (e.g., median < 25% inclusion).

PCA on the laboratory-based measurements identified that the initial principal component accounted for 53.1% of the total variance and represented a collective "average" performance. The results of the LASSO regression with the PCA derived measure showed that only a small number of predictors were relevant with sex (100%), height (97.7%), age (93.1%) and all intensity distance (91.1%) featuring in most bootstrap samples (Figure 4). Cohen's f^2 effect size was very small for all training related factors with the largest median value obtained for all intensity distance (f^2 = 0.01).

4. Discussion

We aimed to determine whether self-reported training variables were effective predictors across a range of laboratory-based measures in a heterogenous group of male and female self-classified cyclists. LASSO regression was used to mitigate against overfitting and generation of spurious results. The analyses showed that of all the training variables considered, only total distance covered summing all intensities tended to feature as a predictor; however, the actual predictive contribution to the outcome measures was very small with Cohen's f^2 equal to 0.01. Training intensity, years of experience, level of competition and having a coach were not predictive of any of the performance outcomes measured in this study. Principal component analysis demonstrated that all laboratory-based measures were strongly associated with each other.

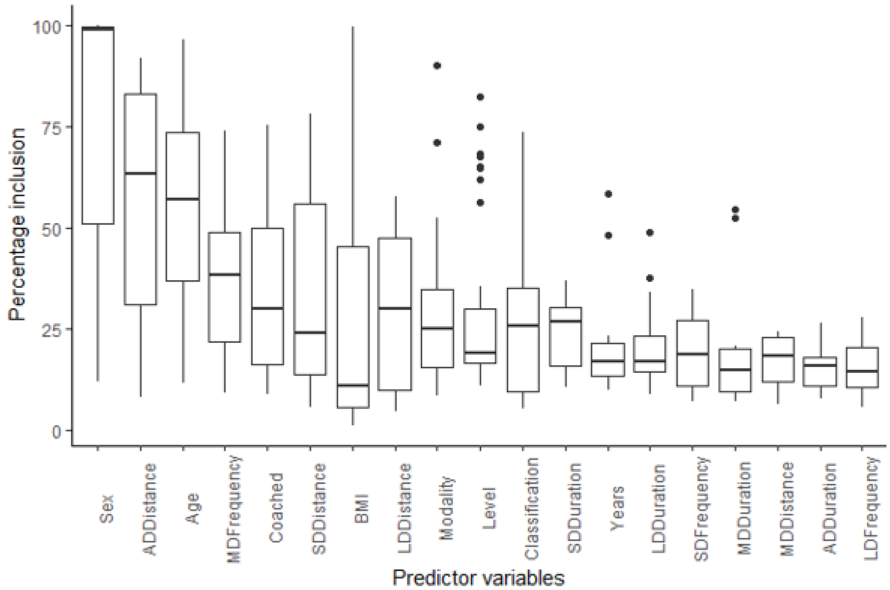

Figure 3: Boxplots illustrating distribution of percentage inclusion in LASSO bootstrap models across all dependent variables. The black line represents the median value, with higher values representing greater percentage inclusion and therefore greater importance in prediction. Legend: ADDistance = all training distance covered, MDFrequency = medium-intensity training frequency, LDDistance = low-intensity training distance covered, SDDuration = high-intensity training duration, SDFrequency = high-intensity training frequency , MDDistance = medium-intensity training distance covered , LDDuration = low-intensity training duration, ADDuration = all training duration , MDDuration = medium-intensity training duration, LDFrequency = low-intensity training frequency, Level = level of competition, BMI = body mass index.

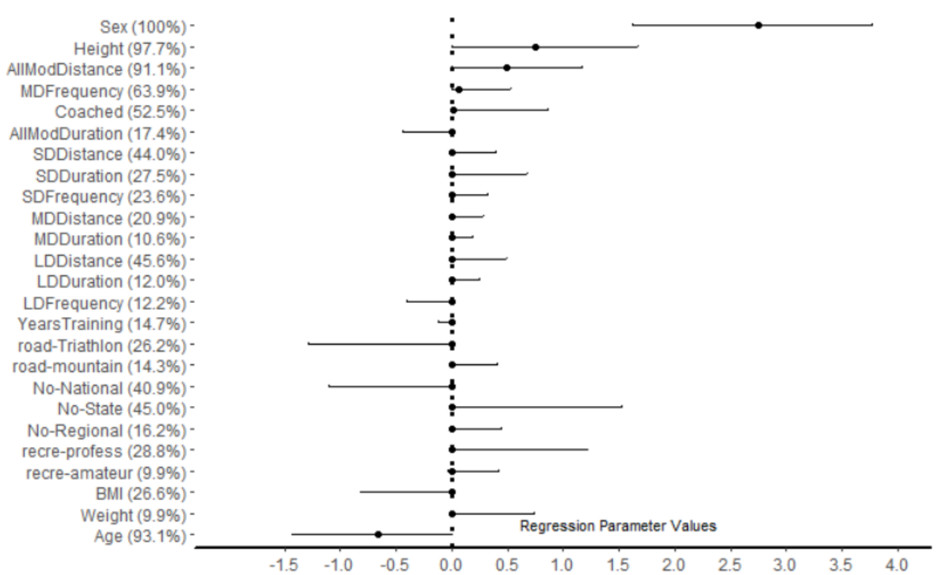

Figure 4: LASSO regression for single dependent variable representing all laboratory-based performance measures according to the PCA analysis weights. Intervals represent 95% confidence intervals for the regression coefficient. Larger regression coefficients and greater percentage inclusion indicates greater importance in prediction. Legend: AllModDistance = all training distance covered, AllModDuration = all training duration , MDDistance = medium-intensity training distance covered, MDDuration = medium-intensity training duration, MDFrequency = medium-intensity training frequency, LDDistance = low-intensity training distance covered, LDDuration = low-intensity training duration, LDFrequency = low-intensity training frequency, SDDistance = high-intensity training distance, SDDuration = high-intensity training duration, SDFrequency = high-intensity training frequency , Level = level of competition, BMI = body mass index, road-triathlon = triathlon modality, road-mountain = mountain bike modality, recre-profess = self-classification as recreational or professional, recre-amateur = self-classification as recreational or amateur , No-National = non-national competitors, No-State = non-state competitors, No-Regional = non-regional competitors.

Table 1: Physical, maximal and submaximal physiological characteristics of male cyclists according to self-reported classification

Characteristic		Total		Recreational		Amateur		Professional	
		n	Mean (SD)	n	Mean (SD)	n	Mean (SD)	n	Mean (SD)
	Age (y)	52	36 (10)	2	42 (0)	45	37 (10)	5	28 (8)
	Height (cm)	52	1.78 (0.06)	2	1.81 (0.01)	45	1.78 (0.07)	5	1.75 (0.03)
	Weight (kg)	52	78.0 (11.1)	2	84.5 (0.07)	45	78.3 (11.5) [a]	5	72.0 (7.5) [a,b]
	BMI (kg·m²)	52	24.6 (3.1)	2	25.8 (0.4)	45	24.7 (3.3)	5	23.4 (2.0)
	Body fat (%)	49	(13.7) (5.2)	0	-	44	13.9 (5.2)	5	11.3 (4.7)
	Weekly training distance (km)	51	307 (140)	2	75 (35)	44	298 (105) [a]	5	488 (244) [a,b]
	Weekly training duration (hours)	51	10.3 (3.6)	2	7.5 (0.0)	44	10.0 (3.5) [a]	5	14.5 (2.7) [a,b]
Incremental test	VO_{2max} Absolute ($L \cdot min^{-1}$)	52	3.9 (0.5)	2	2.8 (0.2)	45	3.9 (0.5) [a]	5	4.1 (0.3) [a,b]
	VO_{2max} Relative ($ml \cdot kg \cdot min^{-1}$)	52	50.2 (7.9)	2	32.6 (1.8)	45	50.1 (6.7) [a]	5	57.4 (8.9) [a,b]
	W_{max} Absolute (W)	52	291 (38)	2	223.5 (20.5)	45	292.6 (36.8)	5	306.2 (27.9)
	W_{max} Relative (W)	52	3.8 (0.6)	2	2.6 (0.2)	45	3.8 (0.6)	5	4.3 (0.5) [a]
	VT1 (W)	52	187 (41)	2	156.0 (32.5)	45	187.1 (42.3)	5	196.8 (34.6)
	VT2 (W)	52	226 (39)	2	194 (2.8)	45	226.6 (40.8) [a]	5	236.8 (21.3) [a,b]
	VT1 (%aW_{max})	52	64.3 (11.9)	2	71.0 (21.2)	45	63.9 (11.5)	5	65.4 (15.0)
	VT2 (%aW_{max})	52	77.7 (9.4)	2	87.5 (9.2)	45	77.2 (9.4)	5	78.0 (9.8)
Wingate	PPO Absolute (W)	50	1040 (209)	0	-	45	1022 (206)	5	1201 (187)
	PPO Relative ($W \cdot kg^{-1}$)	50	13.6 (2.8)	0	-	45	13.2 (2.6)	5	16.8 (1.5) [b]
	MPO Absolute (W)	49	539.8 (190.3)	0	-	44	520.7 (191.3)	5	708.5 (39.9) [b]
	MPO Relative ($W \cdot kg^{-1}$)	49	7.1 (2.5)	0	-	44	6.7 (2.4)	5	10.0 (1.0) [b]
4-km time-trial	MPO (W)	48	262.8 (44.3)	0	-	43	258.4 (44.5)	5	300.8 (17.0) [b]
	Time-to-complete (s)	48	397.7 (24.8)	0	-	43	400.0 (25.0)	5	377.8 (10.7) [b]

[a] $p < 0.05$ when compared to Recreational group; [b] $p < 0.05$ when compared to Amateur group

Table 2: Physical, maximal and submaximal physiological characteristics of female cyclists according to self-reported classification

Characteristic		Total		Recreational		Amateur	
		n	Mean (SD)	n	Mean	n	Mean (SD)
Age (y)		17	43 (9)	1	41	16	44 (9)
Height (cm)		17	1.63 (0.06)	1	1.60	16	1.63 (0.06)
Weight (kg)		16	60.3 (16.1)	1	59.9	15	60.1 (8.6)
BMI (kg·m²)		16	22.5 (2.3)	1	23.4	15	22.5 (2.5)
Body fat (%)		16	18.1 (5.3)	1	21.5	15	18.3 (5.1)
Weekly training distance (km)		16	281 (109)	1	300	15	281 (112)
Weekly training duration (hours)		16	8.8 (4.5)	1	8	15	9.2 (4.4)
Incremental test	VO_{2max} Absolute ($L \cdot min^{-1}$)	17	2.6 (0.5)	1	2.6	16	2.5 (0.5)
	VO_{2max} Relative ($ml \cdot kg \cdot min^{-1}$)	17	42.6 (6.8)	1	43.3	16	42.6 (7.0)
	W_{max} Absolute (W)	17	200 (31)	1	217	16	198 (32)
	W_{max} Relative (W)	17	3.3 (0.5)	1	3.6	16	3.3 (0.5)
	VT1 (W)	17	122 (21)	1	135	16	122 (22)
	VT2 (W)	17	144 (21)	1	156	16	143 (21)
	VT1 (%aW_{max})	17	61.6 (6.8)	1	62.0	16	61.6 (7.0)
	VT2 (%aW_{max})	17	73.0 (6.6)	1	72.0	16	72.8 (6.9)
Wingate	PPO Absolute (W)	14	547.5 (249.8)	1	596.1	13	543.7 (102.5)
	PPO Relative ($W \cdot kg^{-1}$)	14	9.3 (1.4)	1	10.0	13	9.2 (1.5)
	MPO Absolute (W)	14	394.6 (73.0)	1	426.2	13	392.1 (75.4)
	MPO Relative ($W \cdot kg^{-1}$)	14	5.5 (2.8)	1	7.1	13	5.8 (2.6)
4-km time-trial	MPO (W)	16	172.8 (31.7)	1	197.0	15	168.5 (27.3)
	Time-to-complete (s)	16	460.8 (38.5)	1	431.0	15	466.7 (36.7)

Self-reported total weekly distance (km) was the primary training variable included in most of the LASSO models suggesting that cumulative weekly distance covered may be the most important training variable for any individual to consider. A large training volume is considered critical for endurance performance (Laursen, 2010) making it logical that the more cycling performed, the better the physiological and performance measures, although the actual prediction contribution here was low. No men reported cycling less than 50 km per week, which would categorise them as untrained according to distance-based classification (<60 km) (De Pauw et al., 2013), however, 12 men were classified as untrained according to their VO_{2max}. Of these, almost 60% reported covering more than 150 km per week (which would classify them at least as "trained" according to distance), which appears to somewhat contrast our finding that distance covered per week is a predictor of VO_{2max}. This may be due to an absence of a properly implemented training regime, meaning that, while more distance led to greater increases in maximal oxygen uptake, the absolute benefits were less than with a well-structured program. Increases in total training volume correlate well with improvements in physiological and performance variables (Seiler, 2010) and, although the data suggest low predictive ability here in our heterogenous group of cyclists, our results support the notion that athletes might look to increase their total training volume to improve these measured parameters. These data should be confirmed by further studies using objective training metrics obtained from GPS systems.

Aside from total distance covered per week, the predictive power of which was weak, no other training variable assessed here predicted performance. Approximately 50% of weekly training was reported to be at low intensity, a substantial proportion at moderate intensity (~37%) and the remaining at high intensity (~17% for men and ~11% for women). However, training volume at the different intensities were not found to be predictors of these laboratory measures, suggesting that more intense work does not necessarily return greater laboratory-performance parameters herein. The importance of high-intensity training for adaptation and performance is well-known (Laursen & Jenkins, 2002), and thus it could be speculated that the results here may be due, at least in part, to inaccuracies in self-reporting training variables. Any confusion about the questionnaire was resolved via discussion with the researchers, and we attempted to educate the volunteers on the different training intensities to minimise any possible errors. Nonetheless, studies have shown that most individuals tend to overestimate the amount of physical activity they actually perform (Downs, Van Hoomissen, Lafrenz, & Julka, 2014) while the quantification of intensity distribution assessed herein likely adds another level of complexity. Individuals might differ in their interpretation of their own intensity zones, meaning they may not accurately categorise their own habitual training intensities, over- or underestimating the true intensity (and subsequently time spent within these zones, distance covered, etc) of their training. Our data raise the potential that athletes cannot accurately quantify their own training intensities, something that coaches should contemplate when prescribing training and may wish to consider educating their athlete. Future studies should objectively measure training characteristics using electronic devices that measure distance, power output and/or heart rate, and determine how well they agree with subjective evaluation of training, as well as their relationship to these measure laboratory variables.

All volunteers self-identified as cyclists, and we further asked them to classify themselves as professional, amateur or recreational. There appears to be a large discrepancy between how studies classify cyclists (i.e., “trained”, “well-trained”, “professional”, etc), since classification of training status of volunteers is not usually performed using an objective and/or universal system. This has led to the creation of a framework based upon available literature to classify volunteers according to several parameters, the most appropriate of which was deeme

rVO_{2max} (De Pauw et al., 2013; Decroix et al., 2016). Although self-classification here showed differences between recreational, amateur and professional groups for many laboratory parameters, classification according to rVO_{2max} recommendations (De Pauw et al., 2013; Decroix et al., 2016) showed our population was classified from untrained to well-trained cyclists, with none categorised as professional despite having five professional cyclists. In fact, two of those were only classified as “recreationally trained”. Thus, self-reported classification as a professional cyclist was not a predictor of better performance scores, although this may have been due to the low number of professionals that participated in the study. This could either reflect the limitations of the categorisation method according to recommendations or represent a lower standard among these professionals. Since there are limited number of world-class or elite athletes available for research (Burke, 2017), this provides important information that self-reported classification may not directly reflect the level of the cyclist.

All performance variables across the three tests were strongly associated with each other, suggesting that the physiological components required for each overlap. Physiological and performance gains following either isolated sprint or endurance training are specific to the mode employed; combined sprint (i.e., high-intensity) and endurance (i.e., low-intensity) training leads to sub-optimal performance improvements compared to isolated gains with either training mode (Callister, Shealy, Fleck, & Dudley, 1988). Since the chosen tests have different energy contribution requirements, it could be speculated that strong performance in one test (e.g., endurance test) might not be associated with optimal performance in another (e.g., sprint test) due to specific training adaptations. Nonetheless, our data showed that performance between all tests were positively associated, meaning those individuals that performed better in the aerobic test were also those who performed better in the anaerobic Wingate sprint. It is possible that interference from concurrent sprint and endurance exercise is only important at the highest (elite) level where maximal gains are desired while crossover in the gains obtained from isolated high-intensity or low-intensity training does occur (Gillen et al., 2016).

There are some limitations of this study. Firstly, the questionnaire has not previously been validated and thus, it cannot be ruled out that self-reported training variables obtained via a different question would not yield different results. Various iterations of the questionnaire were developed based on feedback attained during pilot testing, whereby members of the research team, and specifically those with extensive cycling experience, completed and fed-back on the questionnaire. Further work should determine whether individuals can accurately quantify their training intensities/volumes. Participants were not familiarised to the 4-km time-trial prior to completing it and had also performed a 30-s Wingate test 20 min previously. Previous work has shown good reliability between two 4-km time-trial sessions without a familiarisation (Azevedo et al., 2019) while we (Oliveira et al., 2017) and others (Borg et al., 2018) have shown that cyclists may not require a familiarisation to produce reliable results, although we acknowledge this would have strengthened our data.

In conclusion, self-reported training variables were poor predictors of laboratory-based physiological and performance variables in this heterogenous group of cyclists, suggesting that most of the self-reported variables acquired via the questionnaire in this study are not useful pre-screening tools when recruiting volunteers for participation in studies requiring non-elite cyclists. It is acknowledged, however, that most studies will want to employ inclusion criteria prior to participant recruitment and these data suggest that total weekly distance covered is the only variable herein with some predictive power for this. Where objective data is available (e.g., exercise monitoring system), this would likely be preferable. The data do imply that total weekly distance may be an important variable to consider for non-elite cyclists attempting to improve their cycling capacity, and further work should objectively determine this.

Conflict of Interest

The authors declare no conflict of interests.

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A comparison of muscle activity between strict, kipping and butterfly pull-ups

Toby Williamson[1 *], Phil Price[1]

[1]*Faculty of Sport, Allied Health, and Performance Science, St Mary's University, UK*

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ABSTRACT
The kipping pull-up (KPU) and butterfly pull-up (BPU) are variations of the strict pull-up (SPU) where an athlete uses hollow and arched body positions to gain momentum, before accelerating vertically. Understanding the muscle activity of each of these exercises will help coaches better utilise them within a strength and conditioning programme. The aim of this study was to compare upper and lower body muscle activation between the SPU, KPU and BPU during the concentric and eccentric phases of each exercise. 11 participants had surface electromyography data collected from three upper and three lower body muscles while completing each pull-up variation. Peak EMG data from each phase for each muscle from the SPU were used to normalise peak KPU and BPU EMG data. A repeated measures ANOVA with Bonferroni post hoc testing was used to identify significant differences between each variation. The results show significantly reduced muscle activation in the bicep brachii during the concentric ($p < 0.05$; $d = 1.1$) and eccentric ($p < 0.05$; $d = 1.1$) phases of the BPU, when compared to the SPU. Activation of the latissimus dorsi was significantly lower during the concentric phase of the KPU ($p < 0.02$; $d = 1.2$) and eccentric phase ($p < 0.01$; $d = 1.4$) of the BPU in comparison to the SPU. Furthermore, significantly greater muscle activation was shown in the rectus femoris, gluteus maximus and rectus abdominus in both the KPU and BPU, when compared to the SPU. However, results differed within the concentric and eccentric phases. These findings show that both styles of kipping increase lower body muscle activation and decrease upper body activation in comparison to the SPU. Further, due to the different style of kip, the KPU and BPU display different muscle activations during both the concentric and eccentric phases.

1. Introduction

The strict pull-up (SPU) is a popular exercise in many strength and conditioning programmes (Pate, Burgess, Woods, Ross, & Baumgartner, 1993; Woods, Pate, & Burgess, 1992). The pull-up requires the upper limbs to pull the body (which is in a hanging position while gripping onto a fixed bar) vertically until the chin passes the bar (Ronai & Scibek, 2014; Youdas et al., 2010). The biceps brachii (BB) and latissimus dorsi (LD) are the prime movers of the SPU exercise as the glenohumeral joint and elbow joint go through extension and flexion during the concentric phase, respectively, and are considerably more active during the pulling (concentric) and lowering (eccentric) phase of the SPU than other upper body musculature (Dorma, Deakin, & Ness, 2013). Interestingly, Dickie, Faulkner, Barnes and Lark (2017) highlighted that differences in upper body muscle activation are seen when comparing the concentric and eccentric phases of the SPU. Further, changes in approach to performing the SPU exercise has seen changes in muscle activation. In 2010, Youdas et al. examined the effect of hand orientations on muscle activity in seven upper body muscles and found the BB produced higher levels of muscle activity when a supinated grip was used compared to a pronated grip. These studies suggest muscle force contributions to the SPU exercise can differ depending on the phase of the exercise and the approach used.

The kipping pull-up (KPU) is a variation of the SPU, where the lower limbs are incorporated to create a greater impulse via an increase in force over a longer duration. This increase in impulse causes greater momentum and velocity during the concentric phase of the exercise. KPU's have recently gained popularity in physical training communities as they allow more reps to be completed in a shorter amount of time, and can be performed by

*Corresponding Author: Toby Williamson, Faculty of Sport, Allied Health, and Performance Science, St Mary's University, UK, tobywilliamson@hotmail.co.uk

athletes who may not have the upper body strength to perform SPU's. KPUs have been compared to a glide kip in gymnastics (Yamasaki, Gotoh, & Xin, 2010), this is largely due to increased contribution of the lower body, when compared to the SPU (Dinunzio, Porter, Van Scoy, Cordice, & McCulloch, 2018). As a result, upper body muscle contributions have been reported to be reduced in the KPU (Snarr, Hallmark, Casey, Nickerson, & Esco, 2015). Snarr and colleagues (2018) reported a decrease in both BB and LD muscle activation during the KPU when compared to the SPU, suggesting an increased emphasis of hip extension to be a possible cause. Dinunzio et al. (2018) provide support for these claims as they reported increased lower limb joint angles and increased lower limb muscle activation.

Similar to the KPU, another variation of the SPU which has also gained recent popularity is the butterfly pull-up (BPU). The BPU requires an advanced form of kipping, where the athlete performs a more cyclical style of kipping in comparison to the up and back motion used for the KPU. The BPU style of kipping can be performed more quickly, though requires greater whole-body coordination to perform. Because of the involvement of the lower body, it is logical to assume upper body muscle activations during the BPU would also be lower in comparison to the SPU. Further, due to the different kipping strategy, there may be different muscle activation patterns between the KPU and BPU. However, no research has currently investigated the BPU.

The programming of these pull-up variations has often been based on the different adaptations they may develop. Typically, the SPU has been programmed for developing upper body weight-relative muscular strength (Pate et al., 1993) and testing upper body muscular endurance (Ronai & Scibek, 2014), whereas the KPU and BPU are often programmed to improve whole body coordination and for increasing the number of repetitions the athlete can perform. However, little is known regarding the muscular strategies needed to perform the KPU and BPU. This knowledge will provide greater understanding of how these exercises effect key physiological adaptations, such as maximal strength, muscular endurance and hypertrophy, enabling coaches and rehabilitators to make better programming decisions. It is therefore the aim of this study to compare upper and lower body muscle activation between the SPU, KPU and BPU during both the concentric and eccentric phases of the exercise. It is hypothesised that upper body muscle activation will be higher in the SPU, lower body muscle activation will be higher in the KPU and BPU, and the KPU and BPU will display different lower body muscle activations throughout the exercise.

2. Methods

2.1. Participants

Ten males (height = 176.6 ± 9.1 cm, weight = 84.9 ± 6.5 kg, age = 33 ± 6 years) and one female (height = 155 cm, weight = 54.9 kg, age = 31 years) volunteered for the study after being recommended by the head coach of a CrossFit affiliate. The inclusion criteria required participants to be injury free, capable of performing five repetitions of each pull-up variation (competency determined by the head coach) and have a minimum of twelve months experience training at the Crossfit affiliate. Prior to the study, participants provided written, informed consent. The study was approved by the St Mary's University Ethics Committee.

2.2. Procedures

Participants took part in one testing session which was preceded by 48 hours total rest. Before the trial commenced, height (SECA Free Standing Height Measure) and weight (Marsden Weighing Group Portable Scale) were measured. A 10-minute familiarisation of the equipment and procedures was completed before two rounds of a standardised warm up were performed: 250 m row, ten PVC pipe pass throughs, eight kettlebell swings and six banded reverse rows. Following the warm-up, participants completed five repetitions of all three pull-up variations in random order. Each set was followed by 5 minutes rest. Due to its ability to show high muscle activation in a pull-up, a pronated, medium width grip (1.5 times bi-acromial distance) was used for all three variations (Andersen, Fimland, Wiik, Skoglund, & Saeterbakken, 2014). The use of chalk or gymnastic handguards was not permitted. The SPU started in a hanging position with the arms fully extended and feet off the floor. Participants then pulled themselves upward, using only their upper body and without the use of the lower limbs to generate momentum. The top of the repetition was completed when the chin successfully passed over the horizontal line of the bar, before returning to the start point. For the KPU, participants started in the same hanging position (Figure 1a). From the start position they would pull forward with an arched body (extension of the spine and hips – Figure 1b), then back to a hollow position (flexion of the hips – Figure 1c) to generate momentum, before swinging themselves upward with the chin passing over the horizontal line of the bar (Figure 1d). During the descent, they would push backwards and fall down into the hollow position (Figure 1e), before passing though the start point as they completed the next repetition.

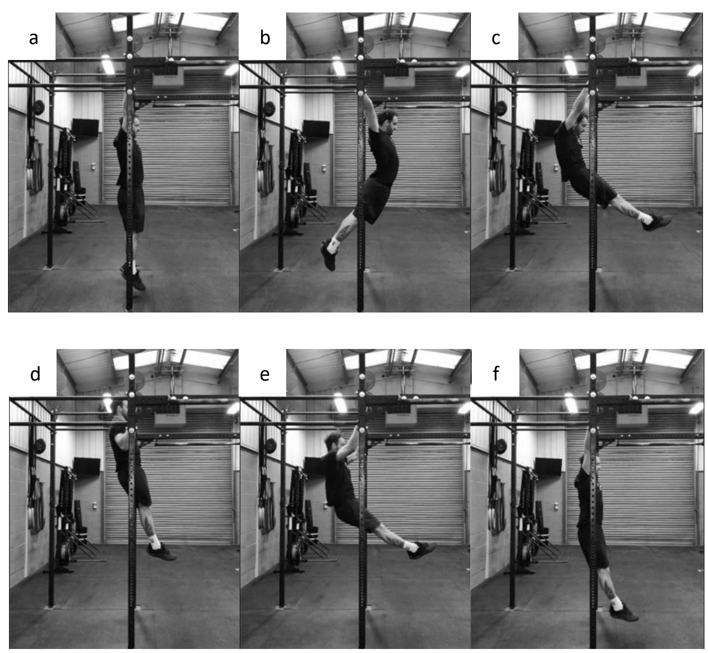

Figure 1: The phases of the kipping pull-up

The BPU also started in the hanging position (Figure 2a). The participant would move into the hollow body shape (Figure 2b) to generate momentum and dynamically pull up to the line of the bar (Figure 2c). On their descent they would pull into the arch position (Figure 2d), before once again passing through the start point (Figure 2e & 2f).

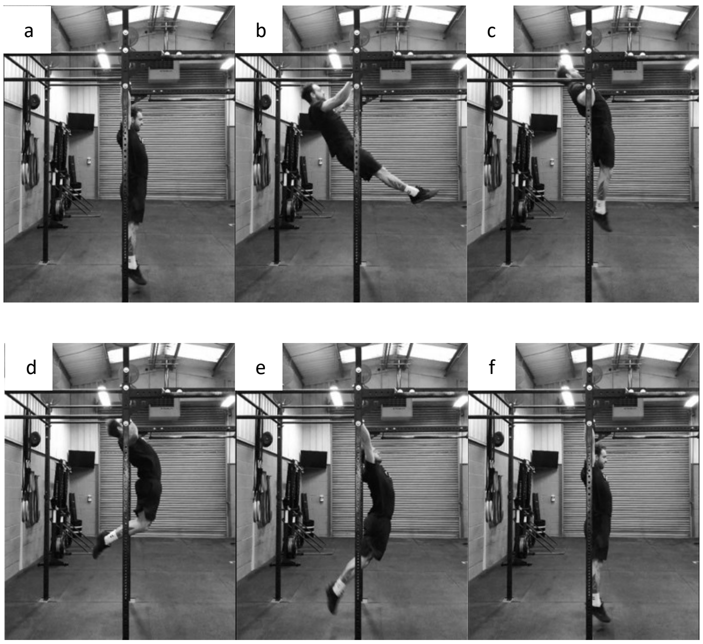

Figure 2: The phases of the butterfly pull-up

A video camera (Panasonic HC-V210 HD camcorder, Panasonic UK Ltd., Berkshire, UK) recording at 50 Hz was placed four metres behind the participant in the frontal plane. The height of the camera was set so that a reflective marker placed on the 7th vertebrae of the cervical portion of the spine was as central as possible when in the hanging start position. The marker was used to identify the concentric and eccentric phases of each exercise. The concentric phase was deemed to have started as soon as the arms were fully extended when descending from the previous repetition with the marker being at its lowest position. The start of the eccentric phase was identified as the moment the athlete began their descent from the peak height achieved when the marker was at its highest position. These kinematic data were analysed using Kinovea analysis software (Kinovea 0.8.15, Kinovea open source, www.kinovea.com).

2.3. Electromyographical Measurement

Electromyographical (EMG) data was recorded using a Delsys Myomonitor® IV Wireless Transmission & Datalogging System (Delsys Inc. Boston, MA, USA) at 1000 Hz. Prior to the application of electrodes, participant's skin was shaved and swabbed. Electrodes were placed on the muscle belly in three upper and three lower body locations, on the participant's dominant side, in line with the muscle fibres. Electrode location followed previous recommendations, which can be seen in Table 1 (Criswell, 2010; Hermens et al., 1999). However, deviation was permitted at the discretion of the lead researcher, when visual identification of the muscle belly differed from recommendations. For example, the muscle belly of the rectus abdominus would often vary between participants in both distance from the xiphoid process and alignment between the linear alba and ribs.

Table 1: Shows electrode location for each muscle and the literature used to identify correct application

Muscle	**Electrode location**	**Reference**
Bicep brachii (BB)	Centre of flexed bicep. 60% of the distance from the fossa cubit and medial acromion.	Hermens et al. (1999)
Latissimus dorsi (LD)	4 cm inferior to the angle of the scapula. 50% of the distance from the vertebrae and the lateral border of the latissimus dorsi.	Criswell (2010)
Infraspinatus (IF)	4 cm inferior to the spine of the scapula, in the middle of the fossa.	Criswell (2010)
Rectus femoris (RF)	50% of the distance from the anterior superior iliac crest to the superior part of the patella.	Hermens et al. (1999)
Gluteus maximus (GM)	50% of the distance from the sacrum to the greater trochanter. In correspondence with the greatest prominence of the buttock.	Hermens et al. (1999)
Rectus abdominus (RA)	50% of the distance from the xiphoid process to the naval. 50% of the distance from the linear alba to the ribs.	Hermens et al. (1999)

2.4. Statistical Approach

EMG readings from repetitions 2-4 were collected in order to eliminate any changes in activation and movement pattern during the swing start of the KPU and BPU (Dinunzio et al., 2018). EMG data for each muscle was individually rectified and smoothed using a 101-point rolling average. The timeframe at which EMG recording began was then identified within the video footage in order to synchronise data sets and define the concentric and eccentric phases of each rep. From here, the peak EMG activations for each phase of all three repetitions where identified and averaged (EMGPEAK). This provided an EMGPEAK for each muscle, across each phase, for all three pull-up variations. Data from the SPU was used to normalise KPU and BPU data (Sousa & Tavares, 2012). EMGPEAK values were presented as a percentage of peak SPU muscle activation, with peak SPU muscle activation displayed at 100%. EMGPEAK values were screened for normality using the Shapiro-Wilk test. Data with normal distribution were analysed using a repeated measures ANOVA using SPSS statistics software (SPSS Inc. Chicago, IL). Non-normal distributed data were analysed using a Friedman's ANOVA. A Bonferroni and Wilcoxon signed-rank post hoc tests were used to identify where significant differences occurred in normal and non-normal distributed data, respectively.

3. Results

The Shapiro-Wilk's test identified that the following variables were non-normally distributed. RF and GM for the concentric phase, and BB, RF, GM, RA for the eccentric phase. The appropriate non-parametric statistical tests were therefore used on these data. Differences in peak muscle activations were shown for both the concentric and eccentric phases of each pull-up variation (Figures 3 to 8). Significant differences in EMGPEAK for the RF (Figure 3) were seen during both the concentric ($X^2 = 16.55$, $p < 0.01$) and eccentric phase ($X^2 = 20.00$, $p < 0.01$). EMGPEAK for the RF was significantly higher in the KPU concentric phase ($Z = -2.93$, $p < 0.01$; $d = 1.2$) and eccentric phase ($Z = -2.93$, $p < 0.01$; $d = 1.3$) in comparison to SPU. RF EMGPEAK was also significantly higher in the BPU in both the concentric phase ($Z = -2.93$, $p < 0.01$; $d = 1.4$) and eccentric phase ($Z = -2.93$, $p < 0.01$; $d = 1.3$) in comparison to SPU. EMGPEAK for the RF for the BPU was significantly higher than the KPU only during the eccentric phase ($Z = -2.93$, $p < 0.01$; $d = 1.1$).

For the BB, significant differences in EMGPEAK during the concentric phase were reported ($F(1.29, 12.95) = 4.23$, $p < 0.05$). Post hoc tests revealed BB EMGPEAK was only lower during the BPU ($p < 0.05$; $d = 1.1$) in comparison to SPU. Significant differences in BB EMGPEAK during the eccentric phase ($X^2 = 16.55$, $p < 0.01$) were also reported. EMGPEAK of the KPU was significantly lower than the SPU ($Z = -2.66$, $p < 0.01$; $d = 1.3$) and the BPU ($Z = -2.93$, $p < 0.01$; $d = 1.3$). These EMGPEAK differences can be seen in Figure 4.

Significant differences were highlighted for RA EMGPEAK (Figure 5) between pull-up variations during both the concentric phase ($F(1.94, 19.39) = 6.36$, $p < 0.05$) and eccentric phase ($X^2 = 14.36$, $p < 0.01$). Post hoc testing for the concentric data found the KPU to have significantly greater EMGPEAK ($p = 0.01$; $d = 1.3$) in comparison to SPU. Post hoc testing for the eccentric phase showed a lower EMGPEAK for the SPU ($Z = -2.93$, $p < 0.01$; $d = 1.6$) and KPU ($Z = -2.85$, $p < 0.01$; $d = 1.2$) when compared to that of the BPU.

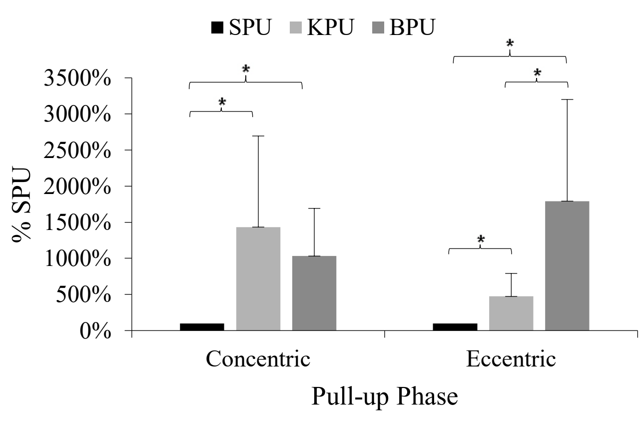

Figure 3: EMGPEAK as % SPU for the rectus femoris across all three variations. Values are given as mean ± SD. * indicates significant difference ($p < 0.05$).

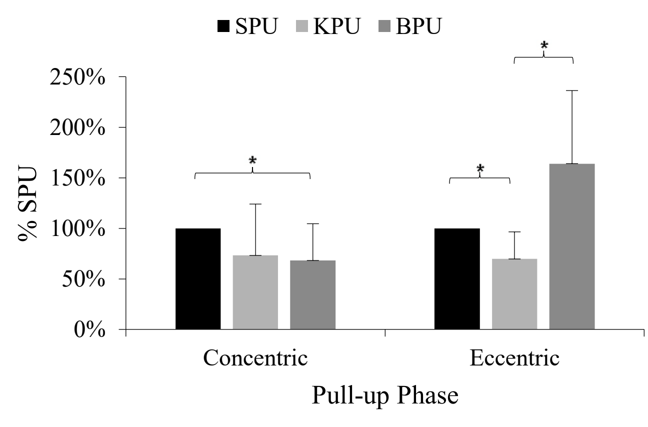

Figure 4: EMGPEAK as % SPU for the bicep brachii across all three variations. Values are given as mean ± SD. * indicates significant difference ($p < 0.05$).

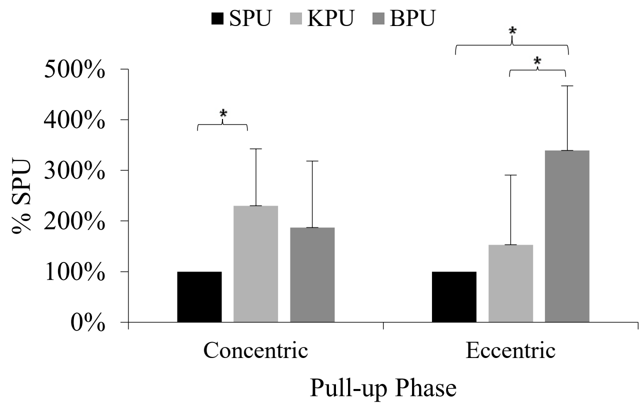

Figure 5: EMGPEAK as % SPU for the rectus abdominus across all three variations. Values are given as mean ± SD. * indicates significant difference ($p < 0.05$).

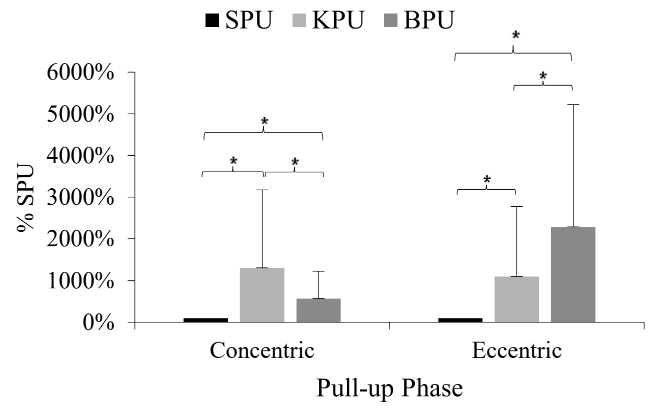

Figure 6: EMGPEAK as % SPU for the gluteus maximus across all three variations. Values are given as mean ± SD. * indicates significant difference ($p < 0.05$).

Significant differences in EMGPEAK for the GM were also reported between pull-up variations during both concentric ($X^2 = 13.27$, $p < 0.01$) and eccentric phases ($X^2 = 20.18$, $p < 0.01$) (Figure 6). GM EMGPEAK was significantly greater during the concentric phase for both the KPU ($Z = -2.85$, $p < 0.01$; $d = 0.8$) and BPU ($Z = -2.40$, $p < 0.05$; $d = 0.9$) in comparison to the SPU. Similarly, GM EMGPEAK was significantly greater for the KPU ($Z = -2.76$, $p < 0.01$; $d = 0.8$) and BPU ($Z = -2.93$, $p < 0.01$; $d = 0.9$) in comparison to the SPU during the eccentric phase.

Significant differences were also reported for LD EMGPEAK during both the concentric ($F(1.92, 19.16) = 5.55$, $p < 0.05$) and eccentric phase ($F(1.79, 17.90) = 14.73$, $p < 0.01$). LD EMGPEAK for the KPU was significantly lower ($p < 0.05$; $d = 1.2$) in comparison to the SPU during the concentric phase. For the eccentric phase LD EMGPEAK for the SPU was greater than both the KPU ($p < 0.01$; $d = 1.5$) and the BPU ($p < 0.01$; $d = 1.4$).

No significant differences were found for IF EMGPEAK during the concentric phase ($F(1.72, 17.17) = 2.27$, $p = 0.14$). However, a significant difference in IF EMGPEAK during the eccentric phase was reported ($F(1.96, 19.85) = 8.20$, $p < 0.01$). IF EMGPEAK for the BPU was significantly higher in comparison both to the KPU ($p < 0.05$; $d = 0.9$) and SPU ($p < 0.05$; $d = 1.2$). No other significant differences were found.

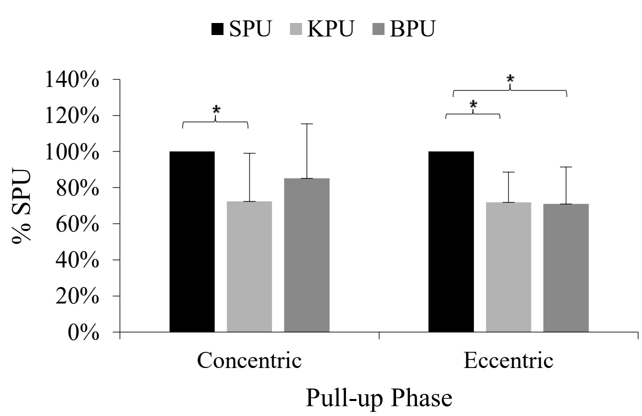

Figure 7: EMGPEAK as % SPU for the latissimus dorsi across all three variations. Values are given as mean ± SD. * indicates significant difference ($p < 0.05$).

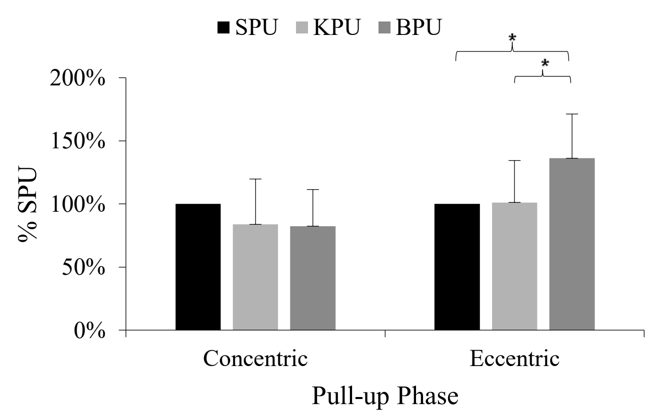

Figure 8: EMGPEAK as % SPU for the infraspinatus across all three variations. Values are given as mean ± SD. * indicates significant difference ($p < 0.05$).

4. Discussion

The purpose of this study was to provide insight into the KPU and BPU in comparison to the SPU. Previous research had shown lower levels of upper body muscle activation in the KPU (Dinunzio et al., 2017; 2018) in comparison to the SPU. However, no research in this area exists for BPUs and it is unknown how muscle activation may differ between the concentric and eccentric phases during all three pull-up variations. The results of this study confirm that both styles of kipping increase lower body muscle activation and decrease upper body activation in comparison to the SPU. It is important to point out that muscle activation was compared to levels shown in the SPU and not a true lower body MVC. Therefore, it is not possible to determine whether a true meaningful stimulus was produced in the lower body. Our findings also suggest that, due to the different style of kip, both the KPU and BPU display different muscle activations. Further, these muscle activation patterns are dependent on the phase of the pull-up. This confirms the hypothesis of this study.

Confirming the findings from Snarr et al. (2018) an increase in lower body muscle activation was found in this study between the KPU and BPU in comparison to the SPU. While significant increases in muscle activation were found in all three lower body muscles, only the RF had elevated levels of activation across both phases in both the KPU and BPU. This increase in activation of the RF is expected, due to the lower body swing when moving between the hollow and arch position (Figure 1b-d and Figure 2b-e) in each style of pull-up. Similar findings were found by Dinunzio et al. (2018) who found the tensor fasciae latae (TFL) and iliopsoas (IL) muscles elicited greater levels of muscle activation during a KPU in comparison to the SPU. As the TFL, IL, and RF all contribute to flexion of the hip (Jiroumaru, Kurihara, & Isaka, 2014), this confirms the role of the hip flexors in generating momentum during the KPU and BPU.

As hypothesized, when absolute load (in this case body mass) is constant, the generation of momentum from the lower limbs during the BPU and KPU resulted in reduced upper limb muscle activation in comparison to the SPU. Both the BB and LD showed significant decreases in muscle activation during the BPU and KPU, though no differences in muscle activation were found between exercises for the IF. These findings compare with Dinunzio, Van Scoy, Porter, Cordice and McCulloch, (2017) who found a reduction in activation of the BB and LD ranging from 5 – 15% MVIC during the KPU. In a more recent study Dinunzio et al. (2018), highlighted the BB as the only upper body muscle to demonstrate reduced muscle activation during the KPU when compared to the SPU. Momentum is generated using the lower limb during the kip, which aids the pulling action from the upper limbs during the concentric phase of the exercise, requiring less muscular effort from muscles such as the BB and LD. This appears to not be true for the BB during the eccentric phase of the pull-up as the style of kip may also influence upper limb muscle activation. As supported by the literature (Dinunzio et al., 2018), BB muscle activation is reduced for the KPU during both the concentric and eccentric phases in comparison to the SPU. However, BB muscle activation during the eccentric phase of the BPU is significantly higher in comparison to both the KPU and, though not significant, the SPU (Figure 4). This is likely due to the body position during the eccentric phase. During the KPU, the athlete moves into a hollowed position (Figure 1e) whereas during the BPU the athlete moves into an arched position (Figure 2e). The arched position likely requires a large contribution from the BB to eccentrically control the lowering of the body, thus the higher BB activation during this phase. This highlights that lower limb momentum does reduce upper body muscle activation during the KPU and BPU, however, the different styles in kipping also influences upper limb muscle activations, most notably during the eccentric phase.

Further analysis of the results of this study also highlight the different lower limb muscle activations seen between the KPU and the BPU. During the concentric phase of the KPU the athlete pulls into an arched position before swinging into a hollowed position as momentum moves the body upwards. In comparison, during the BPU the athlete does not pull into an arched position until the eccentric phase. This would explain why GM activation is significantly greater during the concentric phase of the KPU, and the eccentric phase of the BPU. Further, though not as clear, both the RA and RF show similar activation patterns between exercises. Pulling into the arch position allows these muscles to lengthen, which increases muscle activation and generates the necessary muscle force to swing the legs through, creating momentum for the pulling phase of the exercise. This highlights that both kipping strategies for the KPU and BPU are similar but occur during different phases of the exercises, which alters lower limb muscle activation patterns.

The current study expressed muscle activation as a % of SPU. However, Snarr et al. (2018) presented activation as % MVIC, whereas Dinunzio et al. (2017) presented absolute values with SPU data being subtracted from the KPU and then expressed as a % MVIC. Therefore, the method in which muscle activation is presented differs between studies, which makes the comparison of findings difficult. No kinematic data was recorded in the sagittal plane for this study. As a result, differences in the arched and hollow body positions used in both the KPU and BPU in this study are not objectively known. Further, the participants were allowed to perform all three exercises at a self-selected speed. Participants being able to get into a greater arched position at a greater speed may increase the activation of certain muscles and influenced the results of this study. To minimise this, we recruited participants who have a similar training history with all three exercises. However, having this additional kinematic data would help provide insight to the muscle activation patterns when performing these exercises and further understand the differences between the KPU and BPU.

Conflict of Interest

The authors declare no conflict of interests.

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