Skeleton sled velocity profiles: a novel approach to understand critical aspects of the elite athletes' start phases

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Abstract

The development of velocity across the skeleton start is critical to performance, yet poorly understood. We aimed to understand which components of the sled velocity profile determine performance and how physical abilities influence these components. Thirteen well-trained skeleton athletes (>85% of athletes in the country) performed dry-land push-starts alongside countermovement jump and sprint tests at multiple time-points. A magnet encoder attached to the sled wheel provided velocity profiles, which were characterised using novel performance descriptors. Stepwise regression revealed four variables (pre-load velocity, pre-load distance, load effectiveness, velocity drop) to explain 99% variance in performance (β weights: 1.70, -0.81, 0.25, -0.07, respectively). Sprint times and jump ability were associated (r ± 90% CI) with pre-load velocity (-0.70 ± 0.27 and 0.88 ± 0.14, respectively) and distance (-0.48 ± 0.39 and 0.67 ± 0.29, respectively), however, unclear relationships between both physical measures and load effectiveness (0.33 ± 0.44 and -0.35 ± 0.48, respectively) were observed. Athletes should develop accelerative ability to attain higher velocity earlier on the track. Additionally, the loading phase should not be overlooked and may be more influenced by technique than physical factors. Future studies should utilise this novel approach when evaluating skeleton starts or interventions to enhance performance.

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Key words: acceleration, continuous, ice-track, performance, regression

Introduction

Skeleton is a Winter Olympic sliding sport where athletes initiate a run by sprinting with a bent-over posture whilst pushing a sled (typical mass = 30 to 40 kg) for 20-30 m before 'loading' and adopting a prone driving position. The initial section of the start track must have a declined gradient of 2%, after which the slope becomes substantially steeper and a subsequent 60-m stretch must have a gradient of 12% (IBSF, 2015). A fast start is an important aspect for success in skeleton (Zanoletti, La Torre, Merati, Rampinini, & Impellizzeri, 2006). In light of this, it is surprising that the development of sled velocity during a skeleton push-start has not yet been systematically investigated. Previously, only discrete measures such as dry-land push-track split times (10, 15, 20, 25, 30 m from the starting block; Sands et al., 2005) and ice-track 15- and 45-m velocities (Bullock et al., 2008) have been reported. In isolation, such performance measures have limited utility as these variables do not take into consideration the potentially important transient changes in sled velocity (for example during the loading phase), which are difficult to detect. The influence of these changes on overall performance therefore remains unknown.

Sprint and jump abilities are known to be strongly associated with overall skeleton start performance (Colyer, Stokes, Bilzon, Cardinale, & Salo, in press; Sands et al., 2005). Yet, the differences in the sled velocity profiles between athletes with varying physical capacities have not been investigated to date. Bullock et al. (2008) have previously reported high correlations between 15- and 45- m velocities during ice-track competition (r = 0.71 and 0.67; at Sigulda and St. Moritz ice-tracks, respectively). Thus, athletes who attain higher pre-load (15 m) velocities also tend to have higher post-load velocities, but some unexplained variance exists. This is conceivably due to variation in loading phase success and/or downhill running ability. However, a more detailed analysis of sled velocity during the start phase is required to better understand the sources of this variation. The main aim of this study was, therefore, to investigate the velocity changes across the start phase in order to understand how different aspects of the sled velocity profile contribute to overall start performance. Additionally, key physical characteristics were tested to understand the influence of these individual characteristics on sled velocity profiles. It was hypothesised that sled velocity changes across both the push phase and the loading phase would independently contribute to start performance and that the sled velocity profiles would be influenced by the physical abilities of the athletes.

Methods

Participants

Thirteen well-trained skeleton athletes (8 male and 5 female) participated in this study. This included six athletes, who had competed in multiple World Cup races and/or at the World Championships (two athletes medalled in at least one race) and one athlete who had medalled in multiple races at the European Cup level. The remaining six athletes were development level athletes and were preparing for their first competitive season on the development level circuit. Overall, these athletes represented over 85% of the individuals in the country who were actively training on the dry-land push-track at the time of the study. Participant characteristics (mean ± SD) were: males, age = 24 ± 2 yr, height = 1.76 ± 0.07 m, body mass = 77.8 ± 7.4 kg; females, age = 24 ± 2 yr, height = 1.68 ± 0.06 m, body mass = 66.0 ± 5.7 kg. The University of Bath's Research Ethics Approval Committee for Health (REACH) approved this study (EP 11/12 85). All athletes provided written consent for data to be collected during a series of three 2-day testing sessions across a dry-land training period, as previously described (Colyer et al., in press). Four athletes participated in only two of the three sessions due to illness or injury. Each testing session included dry-land push-track tests followed one hour later by sprint tests, and vertical jump tests were conducted the following morning. Schedules were consistent across testing sessions and participants did not complete any vigorous training in the 36 hours preceding each testing session.

Push-track data collection

An individualised, athlete-led 30-minute competition warm-up was performed prior to each testing session consisting predominantly of running and jumping drills together with stretching exercises. Athletes performed three maximal-effort push-starts from their preferred starting side with a recovery period of at least three minutes between runs. Push-starts were performed by pushing a wheeled sled on an outdoor dry-land push-track. The sled wheels ran along metal rails which were embedded into the surface of the track. A custom-built carbon fibre arm was attached to, and protruded (~0.35 m) the front of, the sled to provide a consistent trigger point for photocells across the track. This was to overcome issues surrounding different body parts interfering with the various photocells across the start phase.

One of the sled wheels was instrumented with a custom-built magnet encoder (Sleed, Sheffield Hallam University, United Kingdom) which provided the time interval for each complete turn of the wheel (every 0.1984 m). These data were telemetrically transferred to a receiver and combined with data from the permanent photocell system (Tag Heuer, Switzerland; 0.001s accuracy). Both data sets were stored using custom-built software (Sleed, Sheffield Hallam University, United Kingdom). Additionally, permanent photocells were situated at the 5-m, 15-m and 55-m marks (Figure 1). The triggering of the 5-m photocell was only used to adjust the Sleed distance data to 5 m, and the actual timing of the start was taken from the 15-m mark photocell in line with skeleton competition timing. Data collection was terminated when the sled interrupted the final photocell at the 55-m mark.. A Sony HC9 video camera (50 Hz at 1/600 s shutter speed) was located next to the track at about 10 m (from the starting block) and was panned to capture footage of the entire start phase. The number of steps taken before loading in each trial was recorded from the video footage.

Sled velocity data processing

Raw sled velocity data were exported from the Sleed software and velocity-distance profiles were derived for each trial. Data were not filtered because time intervals were irregular and thus, did not allow a digital filter to be used (Robertson, Caldwell, Hamill, Kamen, & Whittlesey, 2004). There was, however, some evidence of wheel slippage (an artificial drop in velocity for typically 2 or 3 consecutive points) at set points of the track. This usually occurred on one or two occasions per trial, predominantly in the post-load phase. These data points were excluded from the data set (as opposed to linearly interpolating between points), as this was shown to make very small differences to sled velocities at set distances from the block (< 0.01 m/s) and the distances recorded (< 0.05 m). A typical sled velocity profile is illustrated in Figure 2. The pre-load event was defined as the final data point before a decrease in velocity (indicative of the end of the initial acceleration phase and the start of the loading phase). Additionally, the first data point after the loading phase, following which increases in velocity were approximately constant (i.e. there is no further propulsion from the athlete), was defined as the post-load time-point. The distance and time interval between the pre-load and post-load points were defined as load length and load duration, respectively.

A sixth-order polynomial was fitted from the first data point to ten points following the pre-load time point. This method was preferable to data padding techniques (e.g. linear extrapolation and reflection; Smith, 1989), as based on visual inspection, these other techniques seemed to result in clear and visible errors towards the end-points. Additionally, a linear trend line was fitted to the data from the post-load point to the final data point. Velocity drop during the load was defined as the greatest negative change in velocity across the loading phase (between the pre-load and post-load data points; Figure 2). Load effectiveness was calculated by extrapolating the post-load linear trend line to the pre-load distance and computing the difference between this extrapolated velocity and the actual pre-load velocity.

As previously proposed by Bezodis et al. (2010), measures of performance for discrete sections of sprint-based events should encompass both time and velocity measures. This is because it is unclear whether a more favourable performance is one in which an athlete covers the discrete phase in a shorter period of time or whether attaining a higher velocity at the end of the phase is more beneficial to overall performance. A measure of overall sled acceleration is, therefore, perhaps the most appropriate measure of skeleton start performance in the current study. An important difference between skeleton push-starts and conventional sprint starts in track and field, however, is that the time taken to reach 15 m does not contribute to overall performance in skeleton. Thus, theoretically an athlete can take a longer period of time (attempting to increase impulse during ground contact phases) in the first 15 m in order to attain a higher 15-m velocity. However, the absolute velocity at the end of the start (55-m velocity in this case) is important as this velocity is carried forward into the sliding phase. Thus, a novel sled acceleration index was formulated as follows and used to evaluate overall start performance level:

$$\text{Sled acceleration index} = \frac{\text{55-m velocity}}{\text{Time from 15-55 m}}$$

Physical testing

Sprint and countermovement jump testing was conducted alongside the push-track tests as part of an ongoing monitoring programme. Physical tests were selected based on the strong associations between these measures and start performance which have previously been reported (Colyer et al., in press; Sands et al., 2005). Athletes performed three maximal effort 30-m sprints on an indoor synthetic running track from a three-point starting position. A recovery period of at least three minutes was taken between the runs. A photocell system (Brower Timing System; Utah, USA; 0.001s resolution) was set-up with a timing gate at the 15-m mark at waist height. Timing was initiated when the athlete released their hand from a touch pad placed on the starting line and terminated when the 15-m photocell was interrupted. Time to the 15-m mark was selected as the best measure of sprint ability in this study as previous work has revealed the initial 15 m time to be more strongly associated to start performance than the 15-30 m time (Colyer et al., in press).

Three unloaded countermovement jumps were also performed on a force plate (Fi-tech; Skye, Australia) which sampled vertical ground reaction force data at 600 Hz. At least a two-minute recovery period was taken between efforts. The vertical force (Fz) data were filtered using a low-pass second-order recursive Butterworth filter with a cut-off frequency of 82 Hz derived through residual analyses. Maximum centre of mass displacement (CM_{disp}; from standing height to peak of the jump) was then calculated using the impulse-momentum relationship which has previously demonstrated excellent reliability (Aragón-Vargas, 2000).

Statistical analysis

Mean and standard deviation was calculated for each start performance descriptor and each physical test score (sprint and jump) across the three repeated trials for each athlete at each testing session. In order to assess the ability of the start performance descriptors to predict overall start performance, stepwise multiple regression analysis was conducted on a total of 35 data sets obtained across the training season. Predictor variables included number of steps, pre-load velocity, pre-load distance, load duration, load length, velocity drop and load effectiveness with the criterion variable being the sled acceleration index. Post-load distance and post-load velocity were not included in the model in order to minimise the number of predictor variables, and therefore, maximise statistical power. Additionally, the post-load measures were considered to be unlikely contributors to the predictive model, as these can be largely explained by the pre-load conditions and loading phase variables. Standardised β weights allowed for the comparison of the relative explanatory power of the predictors on the criterion. Entered variables remained in the model, if a significant R^2 (or F-ratio) change was reported. Durbin-Watson statistic and homoscedasticity tests were used to assess for correlation between, and the consistency of, the residual errors, respectively. Variance inflation factors (VIFs) were used to assess the level of collinearity between the independent variables entered into the regression model.

A K-fold cross-validation technique was then adopted to provide a rigorous assessment of the stability of the regression model (Hastie, Tibshirani, & Friedman, 2009). This is particularly useful in small sample sizes when a separate validation data set is not available, as previously adopted (Colyer et al., in press). For this validation method, data are split into K roughly equal-sized parts, a regression model is then fit to $K - 1$ parts and this model is validated against the k^{th} part. This process is then repeated for $k = 1, 2, \ldots, K$. In the current study, each k^{th} part comprised data for one athlete only and therefore $K = 13$. In this way, no validation data set included data from any of the athletes who were used to create the regression model. The correlation coefficient was computed for the relationship between the predicted and actual sled acceleration index and this was compared with the R^2 value of the initial regression model. Generally, a model can be considered stable if the R^2 decrease does not exceed 0.10 (Kleinbaum, Kupper, & Muller, 1988).

Mean and standard deviation was then calculated for start performance descriptor variables recorded for each athlete across all attended testing sessions. Similarly, for all physical test scores undertaken at the same time points as push-starts, mean and standard deviation values were also calculated for each athlete. Pearson correlation coefficients were computed for the relationships between the mean values (n = 13) of the physical test scores (countermovement jump height and 15-m sprint time) and the mean start performance descriptors. Confidence intervals (± 90% CI) for all correlation coefficients were calculated and magnitude based inferences were derived, as previously recommended (Batterham and Hopkins, 2006). A threshold of 0.1 was set for the smallest practically important effect, through which clear and unclear relationships were defined. A relationship was considered positive only, if the *r* value was greater than +0.1 and the lower CI did not cross -0.1, and negative if the *r* value was less than -0.1 and the upper CI did not extend past +0.1. If the CI crossed over both +0.1 and -0.1, relationships were considered unclear. The magnitude of the correlation coefficients were interpreted on the following scale: < 0.1, trivial; 0.1 to 0.3, small; 0.3 to 0.5, moderate; 0.5 to 0.7, large; and > 0.7, very large.

Results

Means and standard deviations of all start performance variables are presented for male and female athletes separately in Table 1. Four variables (pre-load distance, pre-load velocity, velocity drop and load effectiveness) were revealed as significant contributors (significant *F*-ratio change; $p < 0.05$) to the prediction of the sled acceleration index (Table 2). The three variables which were excluded from the model (i.e. those which did not significantly improve the overall fit) were the number of steps before loading, load duration and load length. The overall fit of the model was statistically significant ($R^2 = 0.99$), and thus, these four variables were found to explain 99% of the variance in start performance.

Pre-load velocity was found to explain the greatest portion of variance in the sled acceleration index (71%) and therefore had the highest predictive power out of the four performance descriptors (Table 2). Pre-load distance and load effectiveness explained an additional 22 and 5% of the variance in the sled acceleration index, respectively. The inclusion of the velocity drop in the regression model improved the overall prediction by the smallest amount (1% explained variance), however, the inclusion of this variable still significantly increased ($p = 0.016$) the fit of the model.

The standardised β weights for the four predictive variables (providing the degree to which each predictor affects the outcome variable, when all the effects of the other predictors are held constant) are presented in Figure 3. Higher pre-load velocity and load effectiveness were associated with better start performance, whereas a longer pre-load distance and a larger velocity drop were negatively related to the sled acceleration index. The unstandardised β weights (± 90% confidence intervals) were 0.487 ± 0.019, -0.055 ± 0.005, 0.239 ± 0.049 and -0.067 ± 0.044 for pre-load velocity, pre-load distance, load effectiveness and velocity drop, respectively. These can then be used to form the following regression equation, in which variables can be entered to predict the sled acceleration index (SAI):

$$\text{SAI} = (0.487 \times \text{Pre-load velocity}) - (0.055 \times \text{Pre-load distance}) + (0.239 \times \text{Load effectiveness}) - (0.067 \times \text{Velocity drop}) - 0.125$$

In relation to the aforementioned model, it is worth noting that autocorrelation and multicollinearity analyses showed that the data set was appropriate for multiple regression. A Durbin-Watson statistic of 1.5 indicated that the level of autocorrelation was within the acceptable limits (Field, 2000) and homoscedasticity and normality tests revealed consistent and normally distributed residuals. Variance inflation factors were found to be well below the threshold of 10 (ranging from 1.5 to 3.7), which is considered to indicate problematic levels of multicollinearity (Hair, Black, Babin, & Anderson, 2009). Finally, the *K*-fold validation revealed a strong relationship between the predicted and actual sled acceleration index (R^2 = 0.98) and therefore a small R^2 decrease of 0.01 (1% of the explained variance) was observed from when the model was initially fitted to the entire data set.

Several clear relationships were observed between start performance descriptors and the physical test scores (Figure 4). Faster sprint times were related to longer pre-load distances (*r* = -0.48, 90% CI = -0.78 to 0.00), higher pre-load velocities (*r* = -0.70, 90% CI = -0.88 to -0.34) and better sled acceleration indices (*r* = -0.67, 90% CI = -0.87 to -0.27). Similarly, higher countermovement jump ability was associated with a longer pre-load distance (*r* = 0.67, 90% CI = 0.29 to 0.87), higher pre-load velocity (*r* = 0.88, 90% CI = 0.69 to 0.96) and superior sled acceleration index (*r* = 0.87, 90% CI = 0.67 to 0.95). Interestingly, unclear relationships were observed between both physical test scores and the loading phase performance descriptors (velocity drop and load effectiveness; Figure 4).

Discussion and Implications

This is the first study to investigate a continuous velocity profile of the sled during the skeleton push-start. The instrumented sled wheel provided a unique opportunity to study the transient sled velocity changes during dry-land push-starts in greater detail than has previously been possible. The development of velocity across both the pre-load phase (where the athlete is pushing the sled) and the loading phase independently contributed to the overall success of the skeleton start phase, in line with our hypothesis. Additionally, physical characteristics were shown to influence the velocity and distance at which an athlete loaded the sled, but not the success of the loading phase itself.

Four variables (pre-load velocity, pre-load distance, velocity drop and load effectiveness) were shown to independently contribute to the overall success of the start with high pre-load velocity revealed as the most important factor explaining 71% of the sled acceleration index (SAI). When considered collectively with the observed negative relationship between pre-load distance and the sled acceleration index, better start performances were a consequence of loading the sled with high velocity as early on the track as possible. This likely stemmed from the fact that post-load sled acceleration was primarily dictated by gravity and friction alone (as no driving is required in this phase on the dry-land push-track). Thus, at least theoretically, if an athlete was able to attain the same pre-load sled velocity, but load the sled earlier, then the subsequent increase in velocity (due to gravitational component) across the remaining start phase was maximised.

The results from the regression analysis illustrate the model, which skeleton athletes and coaches should strive for. Long-term training should, therefore, be focussed on enhancing the ability to accelerate, not only to increase an athlete's maximum running velocity, but to attain this earlier in the start phase. However, this may be an over-simplistic model as interactions are likely to exist between the start performance descriptors. In fact, for an athlete to increase pre-load velocity in the short-term (without an advancement in physical capacity), an increase in pre-load distance will typically need to occur. This is to increase the total number of ground contacts through which positive net impulse (in the direction of the track) can be produced in order to increase velocity.

Bullock et al. (2008) have previously reported moderate negative relationships between start time and the number of steps taken before loading on ice-tracks (r = -0.45 at Lake Placid and -0.41 at Sigulda) suggesting that faster starters took a greater number of steps than their slower counterparts on ice. However, the model illustrated in Figure 3 also suggests that for every additional metre taken before loading the sled, the pre-load velocity increase should typically be greater than 0.11 m/s in order to improve the sled acceleration index. This is likely related to the constant influence of gravity on the velocity of the sled after the brow (from about 20-25 m onwards, Figure 1), when the gradient of the declined slope is constant. From the regression model, it may therefore be interpreted that skeleton athletes should accelerate the sled maximally from the block until the sled velocity increments do not surpass those due to the gravitational component (at which time the loading phase should have been initiated). However, this assumes that an individual athletes' ability to load the sled is not affected by an increase in pre-load velocity. This may again be an oversimplification of reality and future studies should experimentally modify the start phase in order to investigate the interactions between pre-load conditions and loading phase success.

The performance potential of an individual athlete on a given day is governed by his/her current physical and mental abilities, and there will be a velocity at which an athlete can no longer generate positive net impulse (in the direction of the track) during progressively shorter ground contact periods. For this reason, physical capacity is likely to regulate the number of steps a skeleton athlete decides to take before loading the sled. Logically, athletes who exhibit superior lower limb power and sprint ability seem to accelerate the sled across a greater distance to attain higher pre-load velocity than their less physically developed counterparts (Figure 4), although inevitably there are also skill elements involved. This may reflect underlying differences in the ability to generate large forces at high velocity, as this appears to be an important determinant of maximum speed in athletic sprinting (Morin et al., 2012; Weyand, Sternlight, Bellizzi, & Wright, 2000). Furthermore, Weyand et al. (2010) suggested that the biological limits to running speed are imposed by the capacity to apply the necessary forces across very short contact periods, rather than simply the maximum force that can be generated by the lower limbs. As maximum running velocity is higher and ground contact times are shorter on declined compared with level surfaces (Weyand et al., 2000), rapid force production may be an even stronger determinant of start performance in skeleton.

The loading phase of the start independently contributed to start phase success. Specifically, load effectiveness was found to positively influence the sled acceleration index (standardised β weight = 0.25), whereas exhibiting a smaller velocity drop unsurprisingly improved start performance (standardised β weight = -0.07, Figure 3), albeit it explained only an additional 1% of the variance in the sled acceleration index. Thus, skeleton athletes should attempt to maximise the overall velocity increase across the loading phase and minimise the velocity drop. A potential mechanism could be trying to limit the extent to which an athlete ‘pulls back’ on the sled during the loading phase. Interestingly, there were unclear relationships between both loading phase variables (load effectiveness and velocity drop) and the physical test scores (Figure 4). This implies that the loading phase may be more dependent on skill-based aspects rather than physical characteristics. Thus, specific loading phase technique training may have utility, when attempting to improve overall skeleton start performance and should perhaps, therefore, be incorporated within skeleton athletes’ training programmes. However, the underlying kinematic and kinetic determinants of superior loading technique and the efficacy of different training methods to optimise this phase, are yet to be explored.

A largely unavoidable limitation to this study, and the majority of other studies conducted in the elite sport setting, relates to the small sample size. However, by definition, the number of elite athletes available to participate in this (and similar) research projects is limited to a small pool of extraordinary performers. This is an even more pertinent issue for studies in sports such as skeleton, where the limited number of facilities and the nature of the sport creates challenges for wider participation. As a result, the participants in this study included 13 out of the 15 performers in the whole country, two of whom had achieved a medal at World Championships or World Cup races.

It has been suggested that the step-wise approach to multiple regression requires great care by the researcher as it may be more susceptible to producing misleading outputs and a confirmatory, forced-entry approach may be more reliable (Hair et al., 2009). However, as this was the first study to analyse the skeleton start using continuous rather than discrete measures of sled velocity, the variables chosen to be included in the regression model (those expected to contribute the most to the prediction of start performance) could not be based on evidence and this analysis was, therefore, primarily exploratory. For this reason, the step-wise method, which sequentially searches for the solution which maximises predictive power of the model, was preferable.

Due to the limited number of participants in this sport, multiple data points from each athlete were included in the regression analysis in the current study to ensure an appropriate ratio between the numbers of observations and predictor variables (at least 5:1) was achieved (Hair et al., 2009; Norman & Streiner, 2003). This may introduce some dependence between data points or clustering of residuals, and could potentially compromise the statistical rigour of this procedure. However, to truly obtain insight regarding elite skeleton start performance, the methods presented here were a necessary compromise. We acknowledged this limitation and tested the data set rigorously prior to conducting the regression analysis. The Durbin-Watson statistic and homoscedasticity tests were used to assess the correlation between, and the consistency of, the residual errors, and revealed the data set to be appropriate for this type of analysis. Additionally, a *K*-fold validation technique demonstrated the excellent stability of the regression model. Thus, the statistical approach adopted in this study and the findings of the regression model appear to be robust.

Conclusion

The current study has used a novel method to uncover new determinants of skeleton start performance. A continuous sled velocity measure allowed the start phase to be characterised in greater detail than was previously possible and a unique sled acceleration index was formulated to overcome the issues associated with conventional start performance measures. The results demonstrated the importance to accelerate the sled more rapidly along with the ability to maximise the overall effectiveness of the loading phase and minimise the velocity drop. These findings also suggest that when approaching the loading phase, it should be ensured that the increments in sled velocity during the final steps surpass the gravitational acceleration component. A positive influence of sprint and vertical jump capacity on pre-load velocity, pre-load distance and the overall sled acceleration index reinforced the essential role of physical training in skeleton athlete development. Notably, although the loading phase independently contributed to the success of the start phase, measures of sprint ability and vertical jump displacement did not seem to influence the success of the load. Thus, separate training to specifically concentrate on enhancing loading technique may therefore be warranted.

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References

Aragón-Vargas, L. F. (2000). Evaluation of four vertical jump tests: Methodology, reliability, validity, and accuracy. *Measurement in Physical Education and Exercise Science, 4*, 215-228.

Bezodis, N. E., Salo, A. I. T., & Trewartha, G. (2010). Choice of sprint start performance measure affects the performance-based ranking within a group of sprinters: Which is the most appropriate measure? *Sports Biomechanics, 9*, 258-269. doi: 10.1080/14763141.2010.538713

Bullock, N., Martin, D. T., Ross, A., Rosemond, D., Holland, T., & Marino, F. E. (2008). Characteristics of the start in women's World Cup skeleton. *Sports Biomechanics, 7*, 351-360. doi: 10.1080/14763140802255796

Colyer, S. L., Stokes, K. A., Bilzon, J. L. J., Cardinale, M., & Salo, A. I. T. (in press). Physical predictors of elite skeleton start performance. *International Journal of Sports Physiology and Performance*. doi: 10.1123/ijspp.2015-0631

Field, A. P. (2000). *Discovering statistics using SPSS for Windows: Advanced techniques for the beginner*. London, UK: SAGE.

Hair, J. F., Black, W. C., Babin, B. J., & Anderson, R. E. (2009). *Multivariate data analysis: A global perspective* (7th ed.). Upper Saddle River, NJ: Pearson.

Hastie, T., Tibshirani, R., & Friedman, J. H. (2009). *The Elements of Statistical Learning: Data Mining, Inference, and Prediction.* (2nd ed.). New York, NY: Springer.

IBSF. (2015). ISBF International Skeleton Rules. Retrieved from http://www.ibsf.org/skeleton/rules.html

Kleinbaum, D. G., Kupper, L. L., & Muller, K. E. (1988). *Applied Regression Analysis and Other Multivariable Methods* (2nd ed.). Boston, MA: Kent Publishing Company.

Morin, J. B., Bourdin, M., Edouard, P., Peyrot, N., Samozino, P., & Lacour, J. R. (2012). Mechanical determinants of 100-m sprint running performance. *European Journal of Applied Physiology, 112,* 3921-3930. doi: 10.1007/s00421-012-2379-8

Norman, G. R., & Streiner, D. L. (2003). *PDQ - Pretty Darned Quick Statistics* (Third ed.). London: BD Decker Inc.

Robertson, D. G. E., Caldwell, G. E., Hamill, J., Kamen, G., & Whittlesey, S. N. (2004). *Research methods in biomechanics*. Champaign, IL: Human Kinetics.

Sands, W. A., Smith, L. S. L., Kivi, D. M. R., McNeal, J. R., Dorman, J. C., Stone, M. H., & Cormie, P. (2005). Anthropometric and physical abilities profiles: US National Skeleton Team. *Sports Biomechanics, 4*, 197-214. doi: 10.1080/14763140508522863

Smith, G. (1989). Padding point extrapolation techniques for the Butterworth digital filter. *Journal of Biomechanics, 22,* 967-971. doi: 10.1016/0021-9290(89)90082-1

Weyand, P. G., Sandell, R. F., Prime, D. N., & Bundle, M. W. (2010). The biological limits to running speed are imposed from the ground up. *Journal of Applied Physiology, 108,* 950-961. doi: 10.1152/japplphysiol.00947.2009

Weyand, P. G., Sternlight, D. B., Bellizzi, M. J., & Wright, S. (2000). Faster top running speeds are achieved with greater ground forces not more rapid leg movements. *Journal of Applied Physiology, 89,* 1991-1999.

Zanoletti, C., La Torre, A., Merati, G., Rampinini, E., & Impellizzeri, F. M. (2006). Relationship between push phase and final race time in skeleton performance. *Journal of Strength and Conditioning Research*, *20*, 579-583. doi: 10.1519/r-17865.1

Table 1. Start performance descriptors (mean ± SD) recorded for male (n = 8) and female (n = 5) skeleton athletes

Start performance descriptor	Male athletes	Female athletes
Number of steps	16 ± 1	16 ± 1
Pre-load velocity (m/s)	8.69 ± 0.45	7.75 ± 0.18
Pre-load distance (m)	26.95 ± 1.84	25.16 ± 1.25
Load effectiveness (m/s)	0.49 ± 0.18	0.55 ± 0.16
Velocity drop (m/s)	0.35 ± 0.20	0.36 ± 0.22
Load length (m)	5.04 ± 0.85	4.14 ± 0.61
Load duration (s)	0.56 ± 0.09	0.52 ± 0.08
Sled acceleration index	2.75 ± 0.11	2.40 ± 0.09

Table 2. Regression model summary for the prediction of the sled acceleration index.

				Change statistics		
Model	Variables entered	*R*	R^2	R^2 change	*F* change	Sig.
1	Pre-load velocity	0.84	0.71	0.71	80.7	<0.001
2	Pre-load distance	0.97	0.93	0.22	109.2	<0.001
3	Load effectiveness	0.99	0.98	0.05	86.4	<0.001
4	Velocity drop	0.99	0.99	0.01	7.6	0.016

Figure Captions

Figure 1. Schematic representation of the push-track set-up. Athletes have a free start from the block; the photocell at the 5-m mark was only used to synchronise the Sleed data; the 15-m mark photocell initiated the actual timing of the start in line with skeleton competition; and data collection finished at the 55-m mark.

Figure 2. A schematic of the sled velocity profile during a skeleton push-start illustrating the identification of the pre-load and post-load time points and the methods used to determine velocity drop, load duration, load length and load effectiveness. N.B. Load duration was calculated across the same section as load length.

Figure 3. A model illustrating the predictors (standardised β weights) of skeleton start performance (sled acceleration index). * denotes significant contribution ($p < 0.01$) to the model. ** denotes significant ($p < 0.001$) contributions to the model.

Figure 4. Pearson (r) correlations between a) 15-m sprint time and b) countermovement jump height and five start performance descriptors. N.B. The axis of the top figure (part a) has been inverted for presentation purposes. Bars represent 90% CI. Shorter dashed lines ($r = \pm 0.1$) indicate thresholds for smallest worthwhile relationships. Longer dashed lines ($r = \pm 0.5$) indicate thresholds for strong relationships. Percentages in brackets represent the likelihoods that the relationships are negative | trivial | positive.

Figure 1

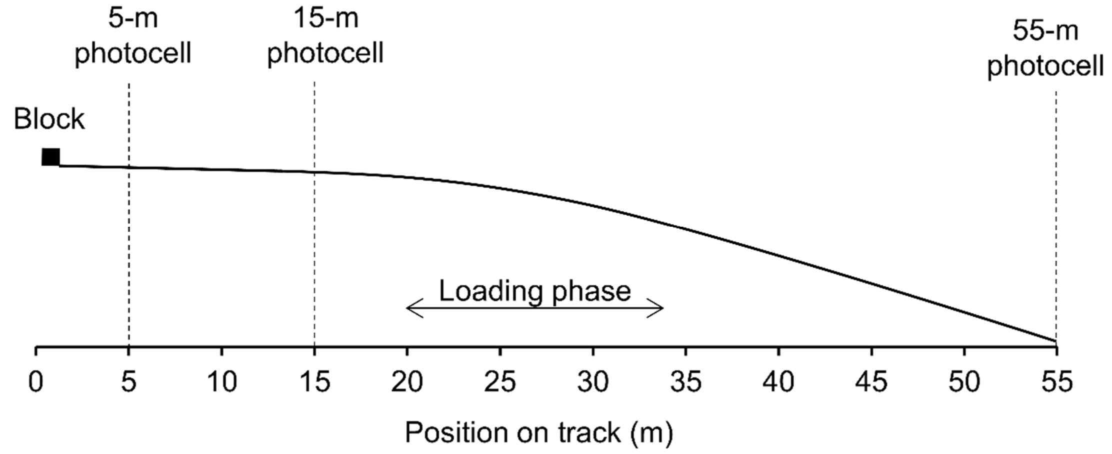


Figure 2

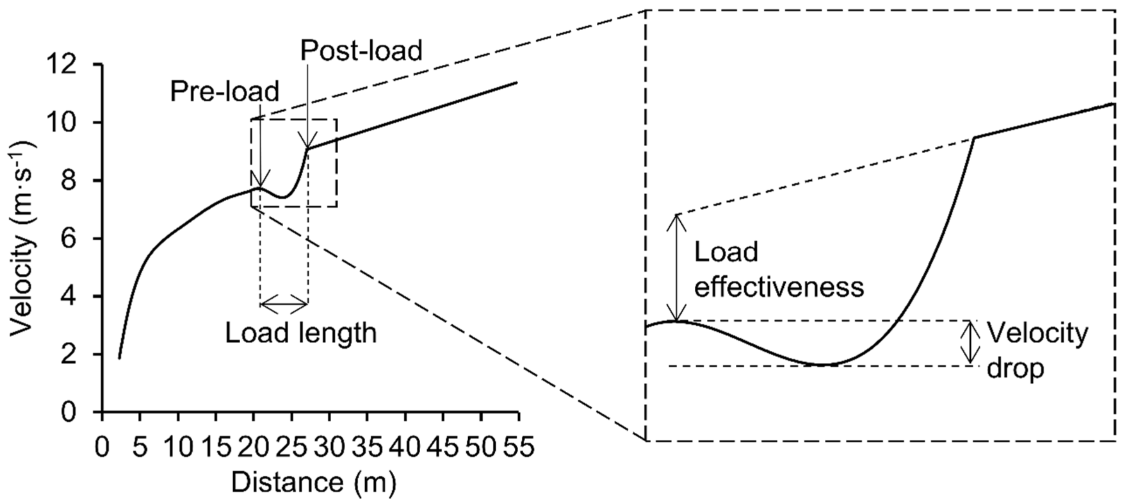


Figure 3

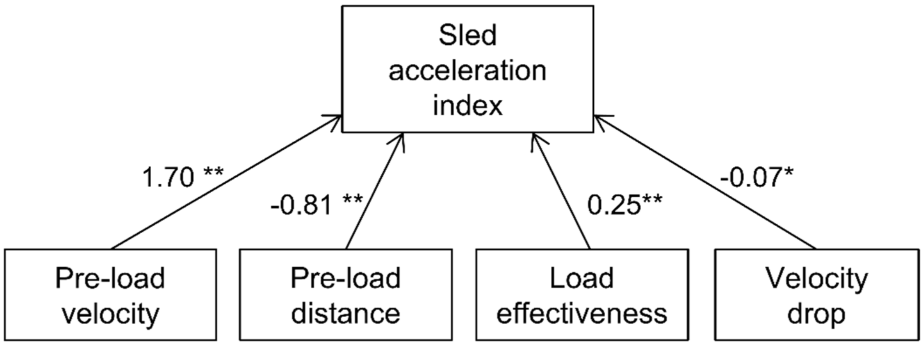
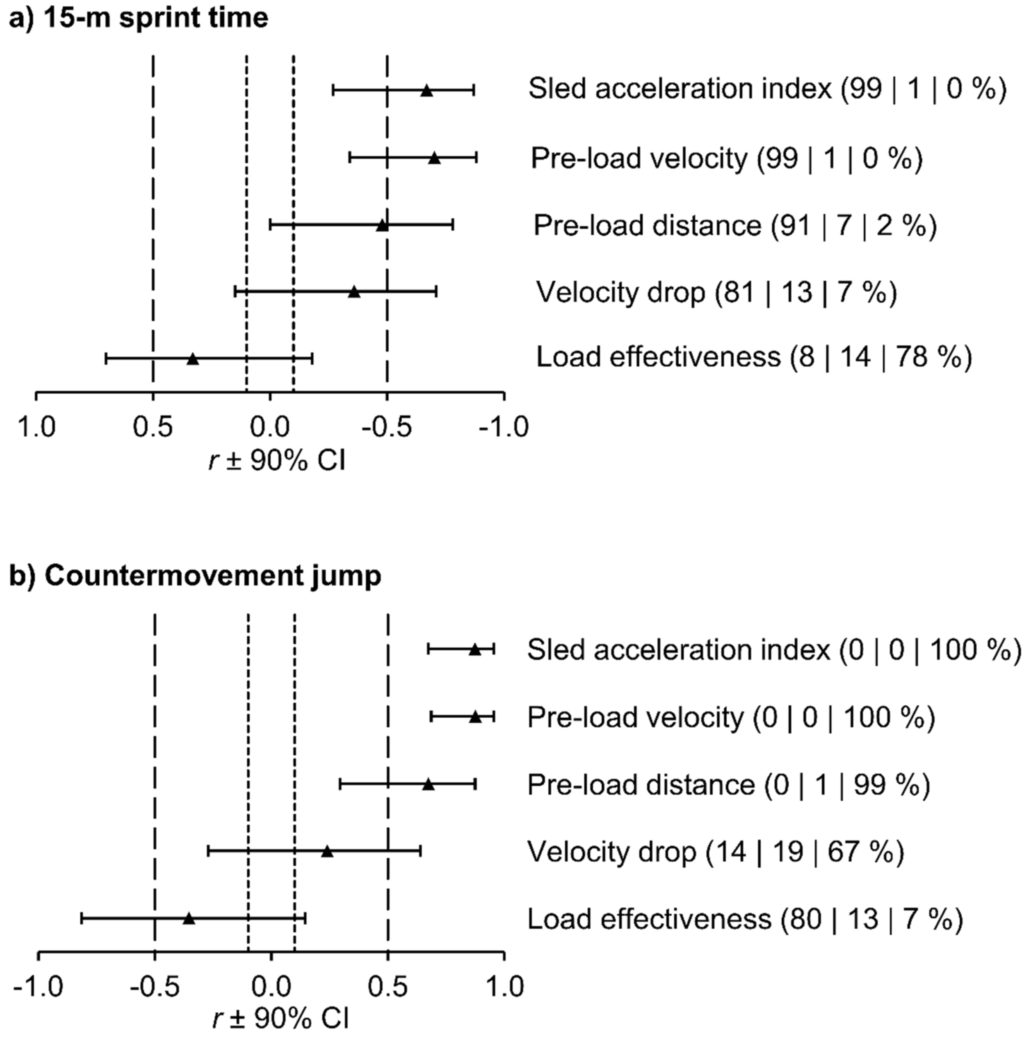


Figure 4


a) 15-m sprint time
Sled acceleration index (99 | 1 | 0 %)
Pre-load velocity (99 | 1 | 0 %)
Pre-load distance (91 | 7 | 2 %)
Velocity drop (81 | 13 | 7 %)
Load effectiveness (8 | 14 | 78 %)
1.0 0.5 0.0 -0.5 -1.0
r ± 90% CI
b) Countermovement jump
Sled acceleration index (0 | 0 | 100 %)
Pre-load velocity (0 | 0 | 100 %)
Pre-load distance (0 | 1 | 99 %)
Velocity drop (14 | 19 | 67 %)
Load effectiveness (80 | 13 | 7 %)
-1.0 -0.5 0.0 0.5 1.0
r ± 90% CI