AUTHOR(S): BARRON, P.-J., BURGESS, K., COOPER, K. and STEWART, A.D.

TITLE: The effect of pitched and vertical ladder ergometer climbing on cardiorespiratory and psychophysical variables.

YEAR: 2018

Publisher citation: BARRON, P.-J., BURGESS, K., COOPER, K. and STEWART, A.D. 2018. The effect of pitched and vertical ladder ergometer climbing on cardiorespiratory and psychophysical variables. Applied ergonomics [online], 66, pages 172-176. Available from: https://doi.org/10.1016/j.apergo.2017.09.001

OpenAIR citation: BARRON, P.-J., BURGESS, K., COOPER, K. and STEWART, A.D. 2018. The effect of pitched and vertical ladder ergometer climbing on cardiorespiratory and psychophysical variables. Applied ergonomics, 66, pages 172-176. Held on OpenAIR [online]. Available from: https://openair.rgu.ac.uk

The effect of pitched and vertical ladder ergometer climbing on cardiorespiratory and psychophysical variables

This study aimed to assess whether modifying the pitch of a 75° ladder ergometer to vertical had a cardiorespiratory or psychophysical effect on climbing. Nine male participants climbed a ladder ergometer at 75° and subsequently at 90°, adjusted for an equivalent vertical climb rate, completing three climbing bouts at different vertical speeds. One participant dropped out being unable to complete the climb under the 90° condition. Each was monitored for heart rate (HR), $\dot{V}O_2$ and rating of perceived exertion (RPE). Results showed vertical climbing induced higher $\dot{V}O_2$ (mean increase 17.3%), higher HR (mean increase 15.8%), and higher RPE at all speeds and that moving from 75°to vertical exacerbates the effect of speed on the cardiorespiratory response to climbing. This may be explained by increased force production required to maintain balance in a vertical climbing position when the body's centre of mass is not above the feet.

Keywords: ladder ergometer; pitched ladder climbing; vertical ladder climbing; ladder climbing physiology

1.0 Introduction

Many occupational roles require employees to climb long vertical ladders for an extended period of time including crane drivers, mast engineers or wind turbine technicians. Research related to energy demands and physiological requirements of professionals in such fields is scarce due to the practical limitations of investigating vertical ladder climbing. These limitations may include: sourcing a suitable venue with the appropriate ladder pitch and length, the cost of shutting active industrial sites down for research purposes, as well as the need to ensure all participants comply with the necessary regulations for working at height. All of these factors impact on the ability of researchers to generate reliable data on the physiology of vertical ladder climbing. An alternative solution is to conduct research on a ladder ergometer, which acts as an endless pitched ladder operating in a manner similar to a treadmill. Ladder ergometers have previously been used in research due to their ability to deliver a constant work requirement, thus enabling steady state oxygen consumption to be achieved at fixed speeds avoiding the challenges and regulations involved when climbing at height.

Ladder ergometers were used in research completed by Kamon (1970), Kamon and Pandolf (1972) and Kamon et al. (1973) when investigating ladder climbing with reported ergometer pitches between 60° and 80°. To date no reported research has been conducted on a vertical ladder ergometer (90° pitch). Currently available ladder ergometers, such as the H/P Cosmos discovery (Nubdorf, Germany) are pitched and unless they are modified, cannot be used to conduct vertical ladder climbing research. As a result, most ladder climbing research has been completed either on short fixed vertical ladders (Milligan 2013, Vi 2008) or on pitched ladder ergometers (Kamon 1970, Kamon and Pandolf 1972 and Kamon et al. 1973).

Vi (2008) conducted a study investigating the difference in energy expenditure and heart rate (HR) when repeatedly ascending and descending a 6.1 m height on both a vertical ladder and a ladder pitched at 75°. Participants were required to climb for at least 5 minutes at a rate which elicited a HR response of either greater than 90 beats per minute or 60% of age-predicted HR max, whichever was lower. Climb rate, recovery interval, total climbing time and test order were not reported, but there was a significant difference between both energy expenditure (11.4 kcal/min v. 13.1 kcal/min) and mean HR (142 bpm v. 155 bpm) when climbing at 75° and 90° respectively. Although the study by Vi (2008) highlighted that climbing at 90° has a larger energetic demand compared to that at 75°, it is unclear as to whether the climbing speed was consistent throughout and how the data were analysed. The use of short ladders with alternating climbing and descent involves a variable energy demand in contrast to prolonged ascending on longer ladders, potentially limiting the generalisability of the study.

This issue was alluded to by Milligan (2013) who suggested the use of short ladders for physiological testing of ladder climbing will fail to show the true demands due to combined ascending and descending the ladder rather than solely ascending. This is most likely due to the partial recovery participants can expect during descending which has a lower physiological demand. Whilst Kamon (1970) found a 26 % decrease in oxygen consumption when descending a ladder ergometer compared to ascending, the recent work of Barron et al. (2016) observed a much greater decrease of 48% in oxygen consumption when comparing when climbing a 30 m vertical ladder.

In summary, data yielded from the extant literature cannot be generalised to long ladders typically used in wind and offshore energy applications, either because the research involved short ladder length mandating alternating ascent and descent cycles, or because of the non-vertical pitch, which potentially lowers the energy cost (Vi 2008). These shortcomings mean such studies are of limited applicability of to a range of professional groups for whom reliable data on energy cost are currently unavailable.

Therefore the aim of this study was to ascertain the effect of altering a ladder ergometer from a pitch of 75° to vertical at three different speeds on $\dot{V}O_2$ consumption, HR, and the rate of perceived exertion (RPE) during ladder climbing. This is important because it could indicate the appropriateness of using existing research on pitched ladders to infer demands of vertical ladder climbing. In addition this study will also assess the demands of steady state vertical ladder climbing at different speeds without the confounding variable of ascending and descending. It was hypothesised that modifying the ladder ergometer to vertical would lead to an increase in $\dot{V}O_2$ consumption, HR and RPE at all speeds.

2.0 Methods and Materials

2.1 Study design and justification

The study was a crossover design with the order of the speeds randomised within each ladder ergometer pitch (Randomizer.org 2015). All participants completed both ladder pitches with the testing at 75° first and the vertical condition second. However, this was unavoidable due to the modification required to make the commercially available pitched ladder ergometer vertical being irreversible. As a result of this modification process, the minimum time between testing sessions was approximately 21 days. The modification involved stabilisation and re-calibration of the ladder ergometer in a vertical orientation, achieved by placing a wedge underneath its base, and new anchors to the floor, walls and roof. All testing took place at the Robert Gordon University, Aberdeen. The School of Health Sciences ethics review panel at Robert Gordon University, Aberdeen approved the study.

2.2 Participants

Nine healthy male participants with no previous ladder climbing experience were recruited from a student population via emails, posters and word of mouth. Eight participants completed the study and their mean demographics are summarised in table 1. Due to the inability to control for menstrual cycle and the unknown nature of the differences between the testing days for pitched and vertical climbing trials, only males were recruited. Although it has generally been seen not to affect aerobic performance (Constantini et al. 2005) the effect is individualised and by only recruiting male participants it removed gender and menstrual cycle as potential confounding factors. All participants completed a pre activity readiness questionnaire (PARQ) and provided informed consent.

Age (years)	Stature (cm)	Mass (kg)	Body Mass Index ($kg.m^{-2}$)
19.8 (±1.7)	178.9 (±6.6)	70.8 (±4.6)	22.1 (±1.4)

Values are mean and SD

Table 1. Physical and demographic data of participants (n =8).

2.3 Experimental protocol

All participants were given a minimum of one familiarisation session on the ladder ergometer (H/P Cosmos discovery, Nubdorf, Germany) which had rung spacing of 24.4 cm and width of 49.5 cm. This session involved 3 x 5 minute bouts of climbing at the test speeds with the ergometer being accelerated up to test speed during the first 30 seconds of the 5 minute exercise bout. The order of the speeds was slowest to fastest for familiarisation. These three speeds for the 75° pitch were slow (9.8 m per minute), medium (12.8 m per minute) and fast (15.4 m per minute). These speeds corresponded to the previous work of Kamon (1970). Participants were deemed to be competent after completing this successfully.

On the first day of testing participants had their stature and mass measured and recorded in accordance with a standard protocol (Stewart et al. 2011). Each Participant was then fitted with a heart rate monitor strap (Polar FI, Kempele, Finland) that was worn for the duration of the testing session. Participants were familiarised with the Borg (1982) 10 point rating of perceived exertion (RPE) scale before completing a five minute warm up at a self-selected climbing rate no greater than 7.5 m per minute. The Borg CR-10 scale was used for its ease of use with fewer points than the 6-20 scale and increased number of anchoring terms. This allowed participants to glance at the scale to obtain a value and maintain concentration when climbing. They then rested for 5 minutes whilst a Cosmed K4 B2 (Cosmed, Rome, Italy) gas analysis system was fitted to them. At this point the participants were informed of the test order of the speeds they would be climbing at. Participants then completed the three 5 minute climbing bouts with 5 minutes' recovery between each. 5 minute exercise bouts were used as at moderate intensity steady state oxygen consumption should be achieved in 3 minutes (Burnley and Jones 2007). Whilst similar studies have used 3 and 5 minutes respectively to achieve steady state oxygen consumption (Bilzon et al. 2001, Milligan 2013). During the last 30s of each bout of climbing participants were asked for their RPE. $\dot{V}O_2$ and HR were averaged over the last minute of each stage.

Between the first and second testing sessions the ladder ergometer was modified altering the pitch from 75° to 90° (As shown in Figure 1.). The speeds climbed were altered to match the vertical height gained when the ladder was pitched, as shown by equation 1. The corresponding speeds for slow, medium and fast speeds were 9.5, 12.4 and 14.9 m per minute.

Figure 1. H/P Cosmos Discovery ladder ergometer pre and post modification.

Participants were familiarised at these speeds following the same process as per the initial familiarisation at 75°.

Vertical speed = (75° climb speed) * (sin 75) [equation 1]

The testing procedure previously outlined for 75° was replicated with the ladder ergometer at 90°. Participants had their stature and mass measured and recorded prior to testing in order to assess for any change in either since the first testing date. The 5 minute self-selected warm up was altered to account for the change in ladder pitch with participants warming up at a rate less than 7.3 m per minute rather than 7.5 m per minute at 75°. No other alterations were made to the testing protocol.

2.4 Statistical analysis

Descriptive statistics were calculated for the sample group and normality assessed using the Kolmogorov-Smirnov test (Field 2012). A sensitivity analysis was run to determine the effect of non-normally distributed variables and the effect of box-Cox transformation in order to determine if variables could be treated as normally distributed. A factorial repeated measures ANOVA was run in order to identify the effect of pitch and speed on HR , $\dot{V}O_2$ and RPE as well as the interaction effect of the two factors, pitch and speed. Mauchley's test was used to assess sphericity and if this was violated, the Greenhouse-Geisser test effect values were used (Field 2012). Significant main effects of ladder pitch were explored using a paired t-test with significance set at $p < 0.017$ due to multiple pairwise comparisons. Effect sizes for the effect of the change on ladder pitch within each speed for HR, $\dot{V}O_2$ were calculated using Cohen's d and interpreted using guidelines set out by Winter, Abt and Nevill (2014).

3.0 Results

The sensitivity analysis suggested all data could be treated as normally distributed. For

$\dot{V}O_2$ there was a significant ($p < 0.05$) main effect for climbing speed, $F(2,14) = 495.8$ as well as climbing angle, $F(1,7) = 79.9$. A significant interaction effect was also found between climbing angle and speed $F(2,14) = 7.8$. Contrasts revealed that climbing vertically significantly increased $\dot{V}O_2$ $F(1,7) = 79.9$ compared to at 75° as well as highlighting that $\dot{V}O_2$ consumption was significantly higher in the fastest speed compared to the slowest in addition to being significantly higher than the medium speed.

Further pairwise analysis, as highlighted in figure 2, was conducted for each speed showing that climbing vertically led to a significant increase $\dot{V}O_2$ consumption. $\dot{V}O_2$ increased by 7.9 (± 1.8) $ml.kg.min^{-1}$ at the slow speed whilst at the medium and fast speeds by 6.3 (±2.2) $ml.kg.min^{-1}$ and 5.1 (± 2.8) $ml.kg.min^{-1}$ respectively. The corresponding effect sizes were all large, as shown in table 2.

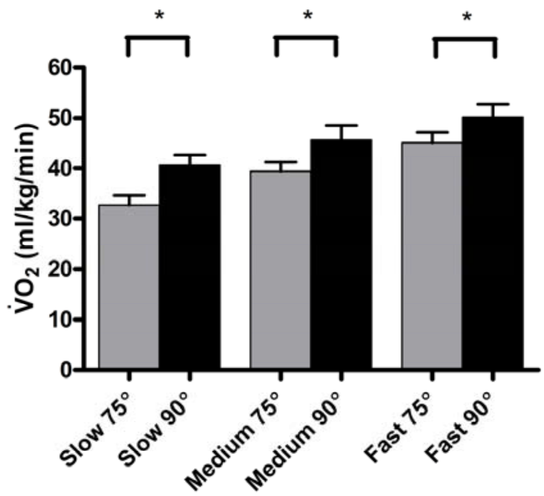

Figure 2. Mean $\dot{V}O_2$ response to the change in ladder ergometer pitch * denotes significance ($p < 0.017$).

Significant main effects for HR were seen for both speed, $F(2,14)= 103.8$; and angle, $F(1,7)= 41.6$ as well as the interaction between the two $F(2,14)= 14.3$. Comparisons showed that HR significantly increased when the speed increased and that it also increased when the angle was changed to 90°. Pairwise analysis, as shown in figure 3, showed that HR significantly ($p < 0.017$) increased at all speeds when climbing vertically compared to when pitched at 75°.

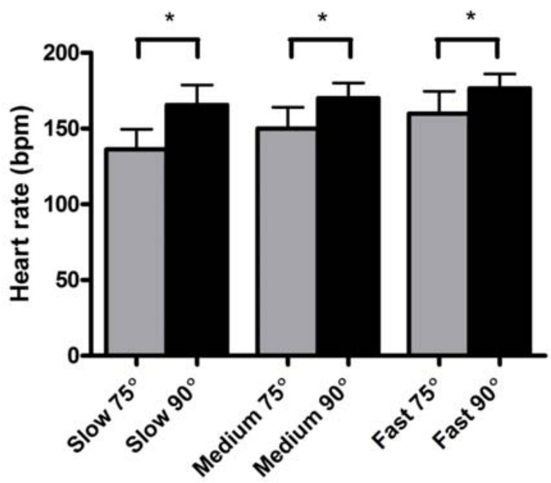

Figure 3. Mean HR response to the change in ladder ergometer pitch * denotes significance ($p < 0.017$).

HR increased by 29.3 (± 10.5) bpm, 20.0 (± 10.0) bpm and 16.7 (± 10.8) bpm for the slow, medium and fast speeds between the conditions. The effect of the change of ladder pitch on HR showed a large effect at all speeds, as shown in table 2.

	$\dot{V}O_2$	Heart rate
Slow	3.3	1.9
Medium	1.9	1.7
Fast	1.7	1.5

Table 2. Effect sizes for change of ladder ergometer pitch on $\dot{V}O_2$ and HR.

The median RPE for the slow, medium and fast speeds at 75° were 1.5, 3.0 and 4.5 respectively. After the ladder was made vertical the median RPE for the three speeds were 4.5, 5.0 and 7.0 respectively. An overall interaction effect was observed whilst further analysis showed an interaction across angle for the medium and fast speeds but not across the slow and medium speed. Significant main effects were seen for both angle and speed. Pairwise analysis showed that modifying the angle of the ladder ergometer significantly increased RPE at the all speeds ($p < 0.017$).

4.0 Discussion

This study aimed to ascertain whether modifying the pitch of a ladder ergometer from 75° to 90° led to a change in the physiological response to ladder ergometer climbing at matched vertical speeds. It was found that climbing in the 90° orientation was associated with significantly higher oxygen consumption across all speeds as well as significantly higher HR in the slow and medium speeds. The mean increase in $\dot{V}O_2$ between the ladder pitch conditions was 17.3% whilst within each of the three speeds $\dot{V}O_2$ increased by 24.5%, 16.0% and 11.5% for slow, medium and fast speeds respectively. In comparison to Kamon (1970) (for similar speeds but at a 60° pitch) the reported $\dot{V}O_2$ values here are higher across all speeds and at both pitches with Kamon (1970) reporting means of 27.0 (± 0.7) $ml.kg.min^{-1}$, 32.9 (± 1.2) $ml.kg.min^{-1}$ and 39.6 (± 2.7) $ml.kg.min^{-1}$ for slow medium and fast speeds respectively. Due to the consistent nature of the speeds between the present study and Kamon (1970) and the lower $\dot{V}O_2$ values reported by Kamon (1970) it is clear that ladder pitch increases the energetic demand of climbing. This may be explained by biomechanical alterations such as height at which the rungs are grasped, the foot-hand distance, the change in the position and movement of the centre of mass and the requirement to maintain balance (Bloswick and Chaffin 1990, Hammer and Schmalz 1992). Hammer and Schmalz (1992) reported that as ladder pitch increased the proportion of time with three points of contact significantly increased, which they hypothesised to be due to the need to maintain balance. Figure 4 shows the change in ladder pitch may alter the centre of mass bringing it outside the base of support as well as reducing the area of the base. Whilst a similar figure was depicted by Hammer and Schmalz (1992) it highlights the displacement of the centre of mass (COM) is due to a change in ladder pitch.

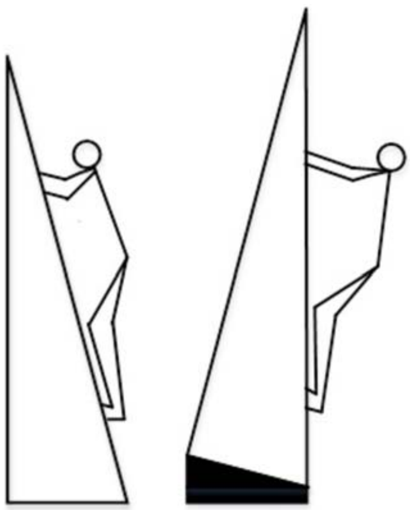

Figure 4. Change in body position in response to ladder ergometer modification.

The change in ladder pitch may alter the mechanical work completed for a given height with climbers having to continually displace their centre of mass vertically upwards. Combined with the COM being outside the base of support, this may lead to increased muscular activation compared to 75° climbing, increasing the physiological cost of climbing. Although this is likely to involve forearm flexors and extensors, electromyographic studies are required in order to confirm this. This increase in demand, shown as increased $\dot{V}O_2$ consumption and HR, may be based on the increased requirement to actively maintain stability due to the position of the centre of mass being outside of the base of support as well as increased mechanical work to move in COM vertically with every climbing cycle. To overcome this change of stimulus climbers adapt their climbing gait and cadence in order to maximise the contact time with ladder to maintain balance (Hammer and Schmalz 1992). The increased contact time and the relative position of the COM to the base could potentially exacerbate forearm stress underpinning localised fatigue or increased EMG readings in vertical climbing (Bloswick and Chaffin 1990, Hammer and Schmalz 1992, Vi 2008). Although not investigated in the present study, this suggests that the need to maintain balance may in part cause greater muscular activation therefore increasing the energy demand of vertical climbing in comparison to pitched ladder climbing.

This current study also supports research conducted by Vi (2008) that vertical ladder climbing has a higher physiological cost than that of a 75° pitched ladder. Vi (2008) reported an 8.5% increase in HR when climbing vertically compared to a pitched ladder which is lower than reported in this study where the mean change was an increase of 15.8%. The current study reported greater increases in HR than those of Vi (2008) with changes of 22.1%, 14.0% and 11.2% being observed from the slowest through to the fastest speed versus 8.5%. There may be numerous reasons for the differences between the results of Vi (2008) and this study, such as the length of ladder, the total duration climbed however, the main influencing factor is potentially the continual 5 minutes of ascending. However, it should be noted that the speed at which Vi (2008) used was not reported and this may differ from the speeds used in this present study. The present study, by the use of a ladder ergometer, had participants ascend for the duration of the exercise bouts rather than alternating ascending and descending a short ladder, as in Vi (2008). Descending a ladder had been shown to reduce $\dot{V}O_2$ consumption by between 23% and 48% compared to ascending (Kamon 1970, Barron et al. 2016) which may partially explain the difference larger difference in the values between this study and those of Vi (2008). Furthermore, Milligan (2013) had individuals climb at 10.52 m per minute eliciting a mean $\dot{V}O_2$ of 28.6 ml/min/kg which is considerably lower than that observed during the 9.52 m per min in the present study of 40.7 ml/kg/min. Although participants in the current study climbed at a faster rate than those in the study of Milligan (2013), the large difference in oxygen utilisation between the studies is most likely explained by the partial recovery during descending involved in their study.

Taken together, the present study supports the premise that vertical ladder climbing does have a greater physiological strain than pitched ladder climbing and that moving from 75°to vertical exacerbates the effect of speed on the physiological response to climbing. It also indirectly highlights the effect that descending may have on physiology-related ladder climbing studies. This underscores the need for specificity in relation to industry requirements, recognising the uniqueness of longer ladder climbing and the physiological consequences of longer ascents, compared to shorter repeated ascents.

4.1 Limitations

There were limitations to the present study. Due to the procedures involved in modifying the ladder ergometer it was not possible to identify specific timings of testing sessions at the two ladder pitches. In practice this was at least three weeks and there was no significant change ($p > 0.05$) in body mass between the 75° and 90° condition for the sample group. In addition, it was not possible to have rails fixed to the ladder ergometer on both sides, and it is appreciated that some wind technicians and other professionals might use rails rather than rungs during climbing in a real life setting.

The speeds used were based on and piloted from work completed by Kamon (1970) which were deemed appropriate for when climbing at 75°. However, when altering the ladder ergometer to 90° these speeds were faster than would potentially be used in the industry. In the present study the medium and fast speed were faster than the recommended and emergency speeds suggested by Milligan (2013). This meant that one participant was unable to complete the full testing protocol at 90°, reducing the sample size available.

4.2 Study implications and future research directions

Climbing vertical ladders incurs a significantly greater energy cost than that for pitched ladders, highlighting the need for specific development on the understanding of vertical ladder climbing. In addition, research on those who climb long vertical ladders should be vocationally relevant. This study only assessed ladder climbing, with no descending, and reported larger $\dot{V}O_2$ values than those climbing at similar speeds but which contained descending. This information is essential for potentially informing the creation of an industry fitness standard, because previous studies underestimate the true severity of continuous ladder climbing. Furthermore, it reinforces the unique nature of climbing vertical ladders which incur a substantially greater physiological cost than pitched ladders.

It is recommended that future research investigates the physiological cost of climbing at vocationally relevant speeds with appropriate personal protective clothing and equipment, and comparing ladder ergometer climbing with in-situ tower climbing.

5.0 Conclusion

Climbing a ladder ergometer at 90° has an increased physiological demand compared to that at 75°. This most likely results from the altered the position of the COM, which necessitates climbers adapt their technique to maintain balance, affecting their contact time with the ladder and increased muscular activation and physiological strain. In contrast to other research (Vi 2008; Milligan 2013) steady state vertical climbing demands higher values of $\dot{V}O_2$ and HR compared to a combination of ascending and descending for the same duration at similar rates. This reinforces the need to ensure specificity for future research aiming to inform policy and standards for a range of industries whose employees climb long vertical ladders.

Acknowledgement

Funded by the Institute for health and Wellbeing Research at Robert Gordon University (Aberdeen) as a PhD studentship. The authors wish to acknowledge the assistance of all participants.

6.0 References

Barron, P.J., Burgess, K., Cooper, K., and Stewart, A.D. 2016. "The physiological effect of a 'climb assist' device on vertical ladder climbing". *Ergonomics*, DOI: 10.1080/00140139.2016.1244290.

Bilzon, J.L.J., Scarpello, E.G, Smith, C., Ravenhill, N.A., and Rayson, M.P. 2001. "Characterization of the metabolic demands of simulated shipboard Royal Navy fire-fighting tasks". *Ergonomics*, 44(8): 766-780. DOI: 10.1080/00140130118253.

Bloswick, D., and D. Chaffin. 1990. "An ergonomic analysis of the ladder climbing activity". *International Journal of Industrial Ergonomics*, 6(1), 17-27. DOI: 10.1016/0169-8141(90)90047-6.

Borg, G., 1982. "Psychophysical bases of perceived exertion". *Medicine and Science in Sports and Exercise Science*, 14 (5), 377 – 381.

Burnley. M., and Jones, A. 2007. "Oxygen uptake kinetics as a determinant of sports performance". *European Journal of Sport Science*, 7 (2), p. 63-79. DOI: 10.1080/17461390701456148

Constantini, NW., Dubnov, G., and Lebrun, CM. 2005. The menstrual cycle and sport performance. *Clinics in Sports Medicine*, 24 (2), p. e51 – e82. DOI: 10.1016/j.csm.2005.01.003

Field., A. 2012. "*Discovering statistics using SPSS*". 3rd ed. London: Sage Publications ltd.

Hammer, W., and Schmalz, U. 1992. "Human behaviour when climbing ladders with varying inclinations". *Safety Science*, 15 (1): 21-38.

Kamon, E., 1970. "Negative and positive work in climbing a laddermill". *Journal of Applied Physiology*, 29(1): 1-5.

Kamon, E., and K.B. Pandolf. 1972. "Maximal aerobic power during laddermill climbing, uphill running and cycling". *Journal of Applied Physiology* 32(4): 467-473.

Milligan, G., 2013. "Fitness Standards for the Maritime and Coastguard Agency and the Oil and Gas Industry". PhD Diss., University of Portsmouth.

Kamon, E., Metz, K.F., and Pandolf, K.B. 1973. "Climbing and cycling with additional weights on the extremities". *Journal of Applied Physiology*, 35(3): 367-370.

Stewart, A., M. Marfell-Jones, T. Olds, and H. de Ridder. 2011. International Standards for Anthropometric Assessment. International Society for the Advancement of Kinanthropometry, Lower Hutt, New Zealand. 125pp.

Vi, P. 2008. "Effects of Ladder Types on Energy Expenditure and Forearm Force Exertion During Ladder Climbing". 2008 National Occupational Injury Research Symposium (NOIRS). Pittsburgh, Pennsylvania. October 21–23 2008.

Winter, E.M., G.A. Abt, and A.M. Nevill. 2014. "Metrics of meaningfulness as opposed to sleights of significance". *Journal of sports sciences* 32(10): 901-902. DOI: 10.1080/02640414.2014.895118.