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The physiological effect of a "climb assist" device on vertical ladder climbing

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The physiological effect of a "climb assist" device on vertical ladder climbing

"Climb assist" claims to reduce strain when climbing ladders; however, no research has yet substantiated this. The purpose of this study was to assess the physiological and psychophysical effects of climb assist on 30 m ladder climbing at a minimum acceptable speed. Eight participants (6 male and 2 female) climbed a 30 m ladder at 24 rungs per minute with and without climb assist, and were monitored for heart rate (HR), $\dot{V}O_2$, and rate of perceived exertion (RPE). All three variables decreased significantly ($p<0.05$) with climb assist with $\dot{V}O_2$ decreasing by 22.5%, HR by 14.8% and RPE decreasing by a mean of 2.3 units on the 10-point Borg scale. When descending the ladder $\dot{V}O_2$ decreased by a mean of 42% compared to that ascending. At the minimal acceptable climbing speed climb assist decreases the physiological strain on climbers, as demonstrated by reduced $\dot{V}O_2$, HR and perceived exertion.

Keywords: ladder climbing; climb assist; vertical ladders; climbing physiology

Practitioner Summary

"Climb assist" systems claim to reduce strain when climbing, however; no research has yet been published to substantiate this. A crossover study compared $\dot{V}O_2$, HR and RPE at a minimal acceptable climbing speed with and without climb assist. Climb assist significantly reduced all variables confirming it reduces strain when climbing.

Introduction

Ladder climbing over an extended period of time is an activity which is performed by employees in many occupations, including crane drivers, radio mast workers and more recently wind turbine workers. Internationally the wind energy market is growing with a global increase in capacity of 17% in the year 2015 compared to 2014, with 268,000 turbines worldwide which must be maintained and serviced to keep them operating optimally (GWEC 2016a, 2016b). Currently 26 countries worldwide have more than 1

MW of installed capacity with many more countries having a lesser capacity, thereby highlighting wind energy as a global industry with turbines on every continent (GWEC 2016b). Wind turbines power more than eight million homes in the UK, 73 million homes across Europe and 110 million across China (GWEC 2016a; Renewable UK 2016). Although more modern turbine designs have lifts to transport workers from ground level to the nacelle (the capsule containing the mechanisms and gearing for the turbine) wind technicians may still be expected to access the nacelle without lift assistance in the event of a malfunction or other emergency. This typically requires individuals to climb up to 80 m vertically in order to carry out such work. Anecdotal evidence suggests individuals in the UK may climb the same turbine up to three times during a repair, representing a 240 m vertical ascent.

As the wind energy sector is relatively young, research around this occupational group is limited with most literature on ladder climbing focusing on healthy populations or construction industry employees. This research has mainly been aimed at understanding forces, climbing biomechanics and slip risk (Armstrong et al. 2009; Bloswick and Chaffin 1990; Pliner, Campbell-Kyureghyan, and Beschorner 2014; Schnorenberg, Campbell-Kyureghyan, and Beschorner 2015) in addition to limited research on the physiological demands of ladder climbing (Kamon 1970; Kamon and Pandolf 1972).

Ladder climbing technique may vary according to personal preference and some evidence suggests that the more climbing an individual does, the stronger the preference for an individualised climbing gait (McIntyre 1983). The main propulsive force is provided by the lower body during climbing with reported mean peak forces produced between 55% and 105% of body weight (Bloswick and Chaffin 1990; Armstrong et al. 2009). Current research on ladder climbing is limited, particularly in relation to vertical ladders. However, previous work has demonstrated that forces are significantly greater during vertical ladder climbing than those produced when climbing a ladder pitched 10° from vertical (Bloswick and Chaffin 1990). Greater horizontal forces relate to the difference of position of the centre of mass relative to the ladder. When climbing a pitched ladder the centre of mass may be directly above the feet whilst in a vertical ladder the centre of mass falls outwith the base of support. This requires continuous force exertion to oppose backwards rotation of the body in order to maintain a stable posture and preventing falling (Armstrong et al. 2009). While the majority of ladder climbing research has focused on biomechanics, slip risk and injury, the physiological demand of ladder climbing by comparison has received very little attention.

Although research on the physiological demands has been conducted on short ladders, pitched ladders and ladder ergometers climbing at 60° over short time periods (Kamon 1970; Kamon and Pandolf 1972; Milligan 2013), this is not generally applicable to the wind energy industry or similar industries which require individuals to climb long, and vertical ladders. Whilst the prior research provides a guideline for the intensity of ladder climbing, there has been little development of ladder climbing research since the work conducted by Kamon (1970) and Kamon and Pandolf (1972). This presents a problem, because vertical ladder climbing incurs greater physiological cost than pitched ladder climbing (Vi 2008) and forces produced at the hands and feet differ (Armstrong et al. 2009). Milligan (2013) investigated the metabolic cost of vertical ladder climbing which involved ascending and descending a 3 m ladder and, while informative, this approach is not equivalent to much larger vertical ascents, due to the partial recovery preventing steady state oxygen consumption being achieved and the altered biomechanics of descending. Currently a gap in the knowledge exists as to the physiological demand placed on climbers over long periods of time, applicable to a variety of contemporary occupations.

To date no research has investigated the physiological demands of vertical ladder climbing equivalent to the task of climbing typical wind turbines. However, in response to the needs of the industry ‘climb assist’ systems have been developed in an attempt to reduce the climbing effort when servicing wind turbines. Such systems operate with a climber secured to a powered steel cable that delivers mechanical uplift to aid upward progress as shown in figure 1. [Figure 1 near here]

The system is responsive to climbing speed and the level of assistance is adjustable. These purport to reduce the load by up to 90% of body mass (between 25-126 kg depending on the manufacturer [Capital Safety 2015; Limpet Technology 2015]). In addition to these claims, typical promotional expressions include their ability to “reduce worker fatigue” or “increasing productivity and asset availability” (Siemens Technology 2012; Capital Safety 2015; Limpet Technology 2015). However there is no published research to substantiate such claims, and research in this area could not only fill a gap in the knowledge regarding physiological effort reduction, it might also have the potential to inform practice in an expanding industry. Therefore the aim of this study was to ascertain the effect of the climb assist device on $\dot{V}O_2$ consumption, heart rate, and rating of perceived exertion (RPE) during vertical ladder climbing. It was hypothesised that using climb assist would lead to a reduction in $\dot{V}O_2$ consumption, heart rate and RPE.

Method

Study Design and Justification

The study was a counterbalanced crossover design with randomised order (Randomizer.org 2015). The institutional ethics committee at Robert Gordon University, Aberdeen, approved the study. All testing took place at the Tag training facility, near Oldham, UK.

Participants

Eight healthy participants (six male and two female) with previous ladder climbing experience at the training venue were recruited via convenience sampling by a collaborator Capital Safety Labs, a safety-training provider for the wind energy industry with facilities including a 30 m climbing tower. Physical characteristics are summarised in table 1. All participants completed a pre activity readiness questionnaire (PARQ) and providing informed consent. [Insert Table 1 near here]

Experimental Protocol

Prior to testing all participants had their stature and mass measured and recorded according to a standard protocol (Stewart et al. 2011). Participants were randomly assigned to climb assist or no climb assist order first with one trial of each being completed. Prior to testing, participants were familiarised with the Borg RPE scale and fitted with a Polar FT90 (Polar Fi, Finland) heart rate monitor for the duration of the testing session. Participants wore a full body harness (Capital Safety, United Kingdom) which was connected to a fall arrest system at all times when climbing. Participants warmed up without climb assist guided by a metronome set at 24 rungs per minute, the minimum acceptable climbing rate for the oil & gas industry (Milligan 2013) for 3 - 5 minutes. Participants then rested for 5 minutes while a Cosmed K4 B2 gas analysis system (Cosmed, Italy) was fitted before initiating data collection. The climb assist system used throughout was the “Powered Climb Assist Tower Kit” (Capital Safety, United Kingdom) as depicted in figure 2. [Figure 2 near here]. The level of climb assist was set to 35 kg for most participants, although the heaviest and lightest participants (122.6 and 54.4kg respectively) selected 55 kg and 22 kg, respectively. The mean assistance was equivalent to 42.3% of body weight. The climb assist system was connected to the participants at the hip contact points on the harness when in use.

Participants then ascended and descended a 30 m ladder inside a wind turbine guided by the metronome at a rate of 24 rungs per minute with each ascent and descent taking a mean time of 3 minutes 45 seconds. The ladder was constructed from aluminium with a rung spacing of 28 cm with the rungs being 42 cm wide. The cross section of the rung was 2.5 cm high and 3.0 cm deep. $\dot{V}O_2$ consumption and heart rate were measured continuously and data were averaged over the last minute of each ascent and descent. After each climb participants were asked for their RPE for the ascent and descent on the Borg 1-10 scale as shown in figure 3. Participants had a 5 minute rest before repeating the procedure in the second test condition. [Figure 3 near here]

Statistical Analysis

Descriptive statistics were calculated for each gender, further analysis involved pooled data. The Kolmogorov-Smirnov test assessed the normality of variables and paired t-tests were run to assess the difference between the test conditions, with $p<0.05$ as significant. The Wilcoxon signed rank test was used to assess the difference between non-normally distributed variables. Cohen’s d was used to interpret effect (Winter, Abt, and Nevill 2014). Change in RPE was assessed using the Wilcoxon signed ranked test (Vincent and Weir 2012).

Results

The full data set was not available for analysis as technical issues with the Cosmed K4B2 led to an unexpected loss of data. Therefore only 6 pairs of data were available for analysis for both $\dot{V}O_2$ and HR. The implication was that a smaller sample size was available for analysis of HR and $\dot{V}O_2$ however, the data were normally distributed allowing for the use of the paired t-test. Despite this, climb assist significantly decreased the oxygen cost of climbing ($p<0.05$). The mean values for ascending with and without climb assist were 22.0 ±4.3 $ml.kg.min^{-1}$ and 28.3 ± 3.5 $ml.kg.min^{-1}$ (mean ± SD) respectively, as seen in figure 4. Overall, climb assist induced a mean 22.5% reduction in oxygen cost with an effect size of 1.8; a large effect. [Figure 4. Near here] Heart rate decreased significantly from 134 ± 27 beats per minute (bpm) to 114 ± 26 bpm ($p<0.05$) when using climb assist, as seen in figure 4. This was equivalent to an effect size of 0.75; a moderate effect. The mean decrease in heart rate was 14.8% with climb assist and ranged from 0.4 – 25.7%.

The decrease in RPE with climb assist ranged from zero to -3 amongst participants. RPE was significantly lower with climb assist (median = 1) compared to without climb assist (median = 3) ($p<0.05$).

The mean $\dot{V}O_2$ consumed for descending was 13.8 ± 2.4 $ml.kg.min^{-1}$ with climb assist and 15.3 ± 3.7 $ml.kg.min^{-1}$ without climb assist as seen in figure 5. No statistically significant differences were found between climb assist and no climb assist when descending ($p > 0.05$). An effect size of 0.39 was observed demonstrating a small effect on $\dot{V}O_2$. [Figure 5. near here].

There was a statistically significant decrease in heart rate from 111 ± 26 bpm (no climb assist) to 99 ± 27 bpm. This equated to a moderate effect ($d = 0.45$).

RPE was also statistically significantly reduced when descending with climb assist ($p < 0.05$). The median RPE for participants reduced from 2.5 to 1 when using climb assist.

Discussion

Climb assist systems aim to reduce strain when climbing and this study demonstrated that climb assist significantly reduces oxygen consumption, HR and perceived exertion at the minimum acceptable climbing rate. The mean difference between the two conditions was a 22.5% reduction in $\dot{V}O_2$ representing a large effect. A significant reduction in heart rate between the conditions was observed with a 14.9% decrease in heart rate, which was a moderate effect. Whilst these reductions in heart rate and $\dot{V}O_2$ are lower than the level of assist provided by the climb assist system (43% of body mass) the requirement to constantly apply horizontal force to maintain stability may in part explain this difference (Armstrong et al. 2009). Vertical ladder climbing is an activity requiring individuals to repetitively exert forces large enough to displace an individuals' mass vertically from one rung of the ladder to the next. This involves overcoming gravity and accelerating the body's centre of mass vertically. The use of a climb assist device reduces the weight of an individual due to providing upward lift when climbing. It is hypothesised that by reducing the weight of an individual required to be displaced by using climb assist that this in turn would lead to a reduction in force required thus lowering the energy demands when climbing. However, it is noteworthy that the climb assist force is continuous and the climber's effort is discontinuous and this may partly explain why a greater reduction in physiological variables was observed when using climb assist. It could be hypothesised that the changes in $\dot{V}O_2$ and heart rate correspond to decreased muscular activation, in line with reduced force production and cardiac output. However, future research on muscular activation and force production would be required to confirm this.

This is the first study that has investigated vertical ladder climbing over an extended period of time. At 24 rungs per minute the mean $\dot{V}O_2$ was 28.9 ml.kg.min^{-1} higher than that found by Milligan (2013) of 23.6 ml.kg.min^{-1}. This may relate to a difference in continuous vertical climbing duration, as participants in Milligan's study were required to climb up and down a 10-rung ladder for 3 minutes rather than climbing vertically for 3.75 minutes. This would lead to a lower mean value because, as Kamon (1970) reported, the demands of descending a ladder were reported to be 26% of those when ascending. This is in contrast to a 42% decrease in $\dot{V}O_2$ when descending a ladder compared to ascending in the present study. The difference in the values may be due to the range of speeds used by Kamon. In his study, increasing speed exacerbates the difference between the mean oxygen cost of ascending and descending approximately 2.5 times. The overall mean difference was reported as a global percentage value based on regression coefficients of only four participants across all speeds in his study, and is a much greater difference than that found in the present study. Even though such a finding is inevitably limited in terms of generalizability by this small sample, the emerging picture suggests the difference in ladder climbing demand between this study and that of Milligan (2013) is due to systematic differences in the protocol, because Milligan's study required participants to descend a ladder for about 50% of the time for data capture, lowering the mean $\dot{V}O_2$ value. In addition, the duration of climbing in this study allowed for steady state oxygen consumption to be reached at nearly 4 minutes, in line with established steady state recommendations by Bilzon et al. (2001), whereas the shorter 3 minute climb by Milligan may have led to participants not reaching steady state, thus reducing $\dot{V}O_2$ values. Whilst the climbing duration fell short of the suggestion of 4 minutes, the exercise time was near that conducted by Bilzon et al.

(2001). Although Åstrand and Rodhal (1970) suggested five minute exercise bouts were necessary for achieving steady state exercise, Milligan (2013) found that the majority of participants achieved steady state oxygen consumption within 3 minutes. A longer ladder would have allowed for a longer duration at steady state; however, the practical limitations in sourcing a venue with a longer vertical ladder could not be overcome in this study.

This study found a 14.86% (ES = 0.81) decrease in mean heart rate between ascending and descending which is a large effect. $\dot{V}O_2$ results show a larger effect size than that of heart rate (ES = 2.8) when comparing the effect of ladder ascent versus descent. This outcome differs from that of Kamon (1970) who found that heart rate was as high during high speed descending as ascending. However, no heart rate data were published in their study but at lower speeds (similar to those of the present study) the $\dot{V}O_2$ values from two participants appeared to be lower than those in this study (approximately 10-12 ml.kg/min^{-1}). This could be due to the demands being lower as the ascent was at 60° and not 90°. It is not currently known whether or not there is industry concern over the level of fatigue that workers experience when climbing wind turbines repeatedly. This study has shown a reduction in the physiological demands of ladder climbing with a ‘climb assist’ system and logically this should lead to an enhanced ability for wind technicians to recover to near-resting levels, which would, in turn, allow them to commence their tasks sooner once they had finished climbing. Theoretically, this could also have implications for the cumulative climbing height expected of workers in a given day, although further research would be required in order to assess the effect this.

Limitations

Due to the nature of the study and the convenience sampling involved this limited the study's sample size and its generalizability. Only six pairs of data were available for heart rate and $\dot{V}O_2$ comparison due to technical issues with equipment. However, the data were still normally distributed allowing for the use of paired t-tests and effect sizes. Perplexing was a small increase in oxygen cost with climb assist in one individual, who was used to much faster climbing speeds. Individual variability, as in locomotion, in preferred speed is likely to influence oxygen cost and efficiency, which merits further investigation, especially in workers of different size and fitness (Sparrow 2000).

Measuring the effect of climb assist on force vectors, centre of mass and biomechanics would have provided a more complete picture of the effect of climb assist on climbing. However, due to environmental factors it was not possible to measure the appropriate variables to conduct analysis on these topics. However, the nature of the climb assist involves direct force applied to the wearer's main harness karabiner at the hips, in an angle of less than vertical. Therefore, the horizontal component of this angle pulls the wearer towards the ladder. It is acknowledged that further investigation should focus on not solely the physiological impact of climb assist but the potential changes in biomechanics, forces exerted and the centre of mass.

Implications and Future Recommendations

At the minimal acceptable climbing speed as defined by Milligan (2013), climb assist does have a positive impact on climbing performance, decreasing oxygen consumption, heart rate and RPE, suggesting that such a product does aid ladder climbers. However, whilst it shows an effect, further research is required to elucidate the relationship between climb assist and speed of climbing. A larger sample will be required to address this in order to have greater statistical power to detect differences in other variables. As it stands, the present study suggests climb assist reduces strain on workers and may have potential to increase their productivity. A study focusing on this area may prove of particular relevance and importance to the industry as this could highlight whether the climb assist has a fixed impact or an effect which increases in magnitude with climbing speed.

The individual variability of fatigue in response to climbing and recoverability of physiological variables after ascent, and the degree of recovery sufficient for the commencement of maintenance work remain important research questions to be addressed.

The wider reaching effects of climb assist should be investigated in respect of the maximum daily climbing limits and the cumulative effect of climbing. If climbing 240 m without climb assist is the current daily limit, it may be pertinent to determine how many more metres this equates to with climb assist to induce the same level of fatigue.

Conclusion

Climb assist is a new system which shows the potential to benefit both climbers and wind turbine providers by reducing the energetic cost and effort of climbing. At the minimal acceptable climbing rate, the system appears to demonstrate a positive effect on vertical climbing and future research should focus on faster speeds and longer ladders.

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Tables

Table 1 Physical and demographic data of participants

Gender	Age (years)	Stature (cm)	Mass (kg)	Body Mass Index ($kg.m^{-2}$)
Female (n=2)	31.4 (±4.2)	169.8 (±16.8)	64.8 (±14.6)	22.3 (±2.8)
Male (n=6)	39.6 (±12.6)	181.2 (±7.0)	93.8 (±16.3)	28.5 (±6.6)

Values are mean and SD

Figure Titles

Figure 1. Climb assist system (With permission from Capital Safety)

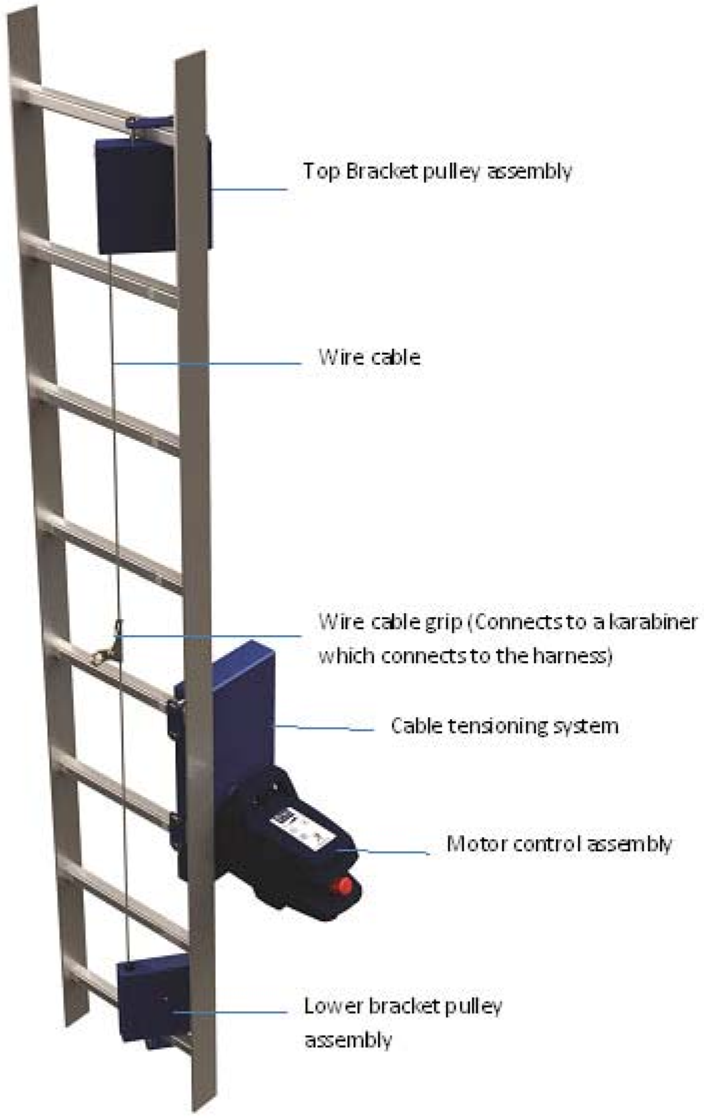

Figure 2. Climb assist system in use (With permission from Capital Safety)

Figure 3. Borg 10 point RPE scale

Rating	Description
0	Nothing at all
0.5	Very, Very Light
1	Very Light
2	Fairly Light
3	Moderate
4	Somewhat Hard
5	Hard
6	
7	Very Hard
8	
9	
10	Very,Very Hard (Maximal)

Figure 4. Mean $\dot{V}O_2$ and HR ascent results (n = 6) * denotes significance ($p < 0.05$)

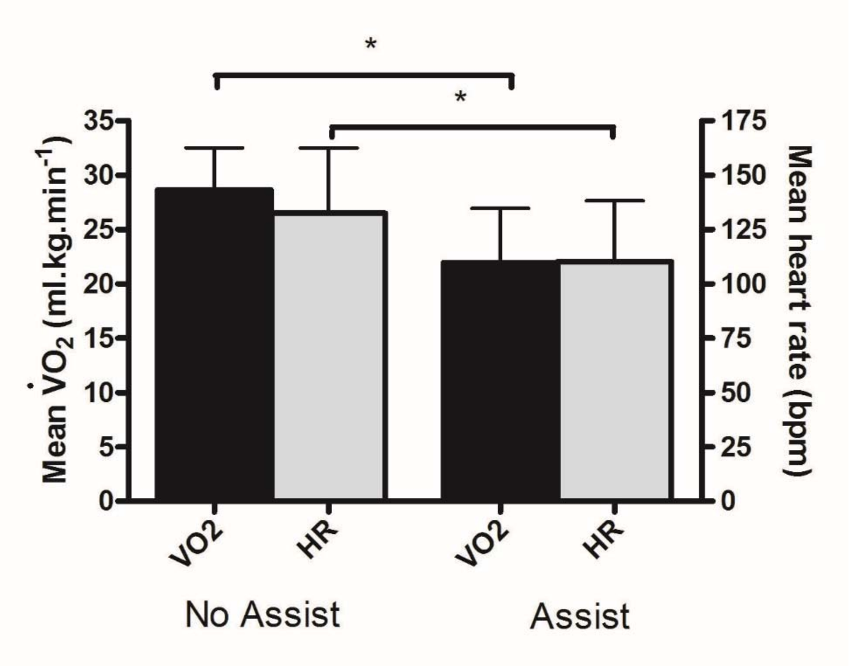

Figure 5. Mean $\dot{V}O_2$ and HR descent results (n = 6) * denotes significance ($p < 0.05$)