A detailed ergonomic assessment of ladder climbing: key risks (short- and long-term) to technicians in the offshore wind industry

G+ Global Offshore Wind
Health & Safety
Organisation

energy institute

A DETAILED ERGONOMIC ASSESSMENT OF LADDER CLIMBING: KEY RISKS (SHORT- AND LONG-TERM) TO TECHNICIANS IN THE OFFSHORE WIND INDUSTRY

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EXECUTIVE SUMMARY

This summary focuses on the practical and policy implications arising from the work undertaken for this project. Those interested in the scientific evidence-base for the conclusions and recommendations reached are referred to the full report, which follows.

The contractual requirements in terms of deliverables for this work were:

1. LITERATURE REVIEW

a. *Objective*: Conduct a review and analysis of the existing literature on ladder climbing, and the effects of this activity on the human body (long and short term).

b. *Methods*: Thirty-four studies were identified and critically reviewed. These examined the biomechanical, physiological, musculoskeletal and other physical health risks associated with repeated climbing of vertical ladders.

c. *Results and Practical Application*: There is a lack of research on the specific ergonomic-related risks associated with working in the wind power industry. Previous assessments on vertical and pitched (from 60° to vertical) ladder climbing have focused on short duration climbs involving multiple ascents and descents. The short nature of the climbs makes it extremely difficult to generalise the findings to Wind Technicians (WT). There is a possibility that the decrements in grip strength observed during ladder climbing could influence the ability of technicians to perform subsequent manual handling tasks. Ladders with unrestricted toe clearance (in the form of space behind the climber), and ladder climbing training programmes, particularly for females and younger and older workers, may reduce of slipping on ladders. Ladder pitch, rest breaks and climbing technique all influence the physical demand associated with ladder climbing.

2. TASK ANALYSIS

a. *Objective*: To determine whether the current industry physical fitness standards are adequate to assess the ability of a technician to undertake the expected level of ladder climbing.

b. *Methods*: The task analysis was completed through: observations of WT performing tasks; the research team undertaking tasks; reviewing operational manuals; using a focus group with an expert panel.

c. *Results and Practical Application*: Five critical tasks were identified as the most physically demanding for WT, these were:

   i. Transfer from the vessel to the Transition Piece (TP) – the type of turbine, sea state and condition of the ladder largely influence the transfer.
   ii. Ascent of the internal ladder – climbing 80 m to 120 m without a time constraint and with the ability to take multiple rests.
   iii. Manoeuvre through hatches – the weight of the hatch door, size and orientation will affect the strength and mobility required for this task.
   iv. Torque and tensioning – lifting up to 19 kg multiple times.
   v. Haul a casualty up the tower – one haul can be up to 4 m before the kit has to be readjusted, the methods of best practice are taught during the Working at Heights and Advanced Working at Heights courses, the mass of casualty is yet to be determined.

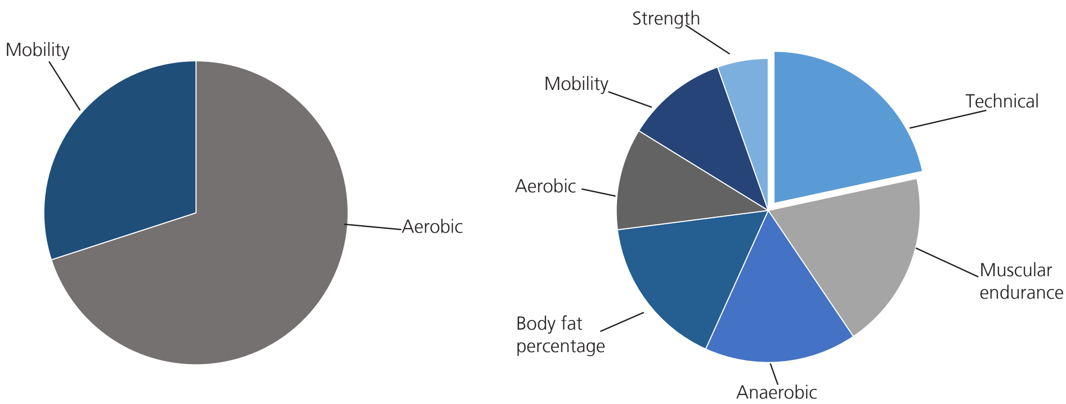
All relevant physical components (e.g. strength, muscular endurance, flexibility) are not assessed by the current medical guidelines, nor is there standardisation across organisations for the assessments that are used (e.g. measurement of aerobic fitness). This critical task analysis can be used to inform decisions regarding the physical fitness requirements, assessments and training that may benefit WT, to ensure they are physical capable of undertaking the critical tasks without undue risk of injury.

3. ERGONOMIC ASSESSMENT

a. *Objective*: To undertake a detailed ergonomic assessment of ladder climbing, identifying the key risks associated, and to determine if the current assessments of fitness are appropriate for predicting ladder climbing ability.

b. *Methods*: Seventeen participants (3 = female; 14 = male) were tested. Of these 10 were novice climbers (1 = female; 9 = male) and seven were current WT (2 = female; 5 = male). Climbers undertook 3 x 120 m climbs separated by approximately 1,5 hrs. Each climb comprised of 4 x 30 m climbs separated by a rest to work schedule of 1:1. For each climb, participants could select their climbing speed and take additional rest when required. Grip strength, grip endurance and performance on a manual dexterity task were measured before and after the 120 m climbs. Three single ascents and descents of the static ladder (approx. 5 rungs) were also undertaken. During the climbs oxygen consumption, heart rate, muscle activation and joint movements were recorded. For the first climb WT (not novices) wore a sea survival suit, all remaining climbs were conducted in overalls, personal protective equipment and climbing harness.

c. *Results and Practical Application*: This is the first study to look at ladder climbing over a distance of 120 m and with repeated climbs throughout the day. The key findings are:
   - Ladder climbing is a combination of multiple components of fitness (Figures 1a and 1b). The comparison of WT to novices showed that technique and experience improve performance, reduce the physiological burden and maintain optimal movement patterns for longer. Therefore, to optimise performance and reduce the risk of injuries, new WT and those that climb infrequently would benefit from training that optimises climbing technique.



Figures 1a and 1b: 1a represents the current fitness components assessed by the wind power industry. 1b shows all the fitness components identified during this study, and their assessed relative contribution to ladder climbing performance

- Wearing a sea survival suit changes movement patterns such that WT are less efficient (increase demand). Therefore, it is recommended that they are only worn when transferring from the vessel to the TP; once inside the turbine they should be removed.
- As fatigue increased with multiple climbs, toe clearance on the ladder was reduced. This has been shown to increase the likelihood of trips and the potential for injury.
- Manual function (strength, endurance and dexterity) was significantly impaired by ladder climbing.
- Changes where observed in the shoulder joint which suggested that as fatigue increased participants changed their technique to reach higher with their arms. The non-ladder climbing literature suggests that such repetitive shoulder movement leads to an increased risk of chronic shoulder injuries.
- Novices demonstrated less range of movement through the hips, and a higher proportion of muscle activation in the upper body than the WT. This means they were using less of the large muscle groups of the legs and more of the small muscles in the arms. Ultimately, this will lead to an earlier onset of fatigue and increase the likelihood of injuries through loss of grip. Efficient ladder climbing technique should be taught.
- The data on muscle activity, grip strength and grip endurance supported the subjective feedback that the reason for resting during the ladder climb was fatigue in the forearms. This fatigue was noted to last several days in some participants, suggesting if large volumes of climbing were to take place on consecutive days cumulative fatigue could impact on performance and increase injury risk, especially in novice climbers or those that do not climb regularly.

4. THERMAL ASPECTS

a. *Objective*: To investigate the effects of heat stress on the technician whilst climbing, and their ability to perform their work safely after multiple ladder climbs.

b. *Methods*: Temperature data were collected on seven WT, during the 3 x 120 m climbs, from these data mechanical efficiency and total heat production were calculated for climbing in a sea survival suit and overalls.

c. *Results and Practical Application*: The mean (standard deviation) mechanical efficiency (work done/energy consumed) during the climbs with the survival suit was 14,6 (3,4) % (85,4 % of the energy consumed being released as heat). The corresponding figures for the overalls was 16,3 (5,12) %. As a comparison, walking is 35 % to 40 % efficient. The best ladder climber achieved a ME that was approximately 5 % higher than the other participants. This was also reflected in a relatively slow rate of rise of deep body temperature in this individual (less heat produced for work done). As an approximate guide, the increase in deep body temperature was used to calculate a time to a given deep body temperature when climbing and resting volitionally; the times to reach a deep body temperature of 38,5 °C are presented in Table 1.

Table 1: Estimated time to reach a deep body temperature of 38,5 °C. Calculated on the basis of direct measurements in the present study, as well as calculated theoretical maximum changes (worst case, no heat loss) from heat production data

Condition	Time to 38,5 °C (min)
Survival Suit using Tpill data from current study	45,5
Overalls using Tpill data from current study	62,5
Survival Suit using calculated worst case scenario (no heat loss)	14,3
Overalls using calculated worst case scenario (no heat loss)	14,2

- WT are likely to settle upon a work/rest schedule that means they can climb 120 m without a direct risk from hyperthermia. More concerning is the indirect risk: that is, impact of heating on discomfort, cardiovascular control and the maintenance of blood pressure. This may lead individuals, particularly if dehydrated, to feel light-headed, excessively fatigued.
- From the thermal perspective, those with responsibility for the well-being of WT should ensure that the technicians have the opportunity to cool down and rehydrate following prolonged ladder climbs e.g. 30 m to 120 m.
- High aerobic fitness and technical ladder climbing skills should be encouraged/taught – these have a directly beneficial impact on the stress and heat production associated with ladder climbing.

Recommendations for future work/considerations

It is recommended that future work focus on three main areas, these are:

1. Training packages – the purpose of which would be to reduce the time taken for novice climbers, and those that climb less frequently, to become proficient at ladder climbing. This would optimise well-being and performance by reducing the onset of fatigue in WT, and thereby the risk of injuries.
2. A review of fitness and selection policies to include assessments of all of the physical fitness components of ladder climbing.
3. Determine the optimal work/rest schedules for WT in order to optimise ladder climbing performance and reduce the risk of potential direct and indirect heat related problems. Review policies on cooling and hydration.

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INTRODUCTION

In September 2015 a fatal incident occurred on an onshore Wind Turbine Generator (WTG) service lift in Germany. Since this incident, a large number of offshore wind operators have prohibited the use of service lifts until the cause of the incident has been disclosed by the investigating German authorities. Whilst use of WTG service lifts is prohibited, or for those out of service due to defects, or if helicopter transfer of technicians is not possible, then any work/fault finding required in the nacelle will require a technician to climb the tower ladder. A typical offshore wind turbine tower can be 80 m to 120 m high, there is little published research examining the effects of ladder climbing in relation to:

- The physiological demand of prolonged ladder climbing.
- Whether the current industry physical fitness standards are adequate for assess a technician's ability to undertake the expected level of ladder climbing.

Therefore, the University of Portsmouth was contracted by G+ Global Offshore Wind health and Safety Organisation (G+) and the Energy Institute (EI) to provide a detailed ergonomics assessment, identifying the key risks to technicians (short- and long-term), associated with ladder climbing in the offshore wind industry according to the following terms of reference:

a. Conduct a review and analysis of existing literature on ladder climbing and the effects of this activity on the human body (short- and long-term). This will include consideration of:
   I. Previous ergonomic assessments performed on ladder climbing.
   II. The physical demands of climbing with respect to musculoskeletal disorders and heat stress.
   III. Whether the current industry physical fitness standards are adequate for assess a technician's ability to undertake the expected level of ladder climbing.
   IV. Consider if there is an increased risk of injury, e.g. hands, as a consequence of increased levels of climbing.
   V. Consider the interaction between ladder climbing and PPE in terms of heat stress and physical capabilities.
b. Review existing design and operational standards for ladders used in the offshore wind industry and identify the key risks to technicians (long term and short term).
c. Undertake an ergonomic assessment of ladder climbing.

The work undertaken and presented within this report is shown in Table 1.

Table 1: Scope of work

Key deliverables	Work covered	Work undertaken
Literature Review (section 1)	Conduct a review and analysis of existing literature on ladder climbing and the effects of this activity on the human body (long term and short term)	Systematic literature review
Task Analysis (section 2)	Review existing design and operational standards for ladders used in the offshore wind industry Whether the current industry physical fitness standards are adequate for assess a technician's ability to undertake the expected level of ladder climbing	Determine through standard operating procedures, questionnaires, focus groups, observation: – Current practices – Methods of Best Practice (MOBP) – Climbing rates – Frequency/Duration – Environmental conditions – Existing Fitness standards – Injury occurrences/rates – What are they? – - When do they occur? i.e. ascent vs – ***This section has been presented in full as the G+ committee for review prior to the submission of the final report***
Ergonomic Assessment (section 3)	Undertake a detailed ergonomics assessment identifying the key risks to technicians (long term and short term) Whether the current industry physical fitness standards are adequate for assess a technician's ability to undertake the expected level of ladder climbing	– Ergonomic and physical assessment (e.g. Opto electric cameras; muscle EMG, measurement of grip strength, Oxygen consumption and heart rate) of climbing a ladder (performed on a ladder treadmill, using the agreed MOBP, for the duration of a ladder climb up a turbine tower – Due to restrictions in the Ladder treadmill and the requirement of the Opto electric cameras to be used in a laboratory environment, ergonomic assessment regarding the decent of a ladder was a discontinuous snap shot using the MOBP
Thermal Aspects (section 4)	The effects of heat stress on the technician whilst climbing and their ability to perform their work safely after multiple ladder climbs	– The impact of ladder climbing was assessed to determine the likely range of individual responses

1 LITERATURE REVIEW

1.1 OBJECTIVE

Conduct a review and analysis of existing literature on ladder climbing and the effects of this activity on the human body (short- and long- term).

1.2 METHODOLOGY: INCLUSION CRITERIA

1.2.1 Participants

Wind technicians (WT), and in the absence of studies of these professionals, participants from firefighting, mining, military and other occupations involving ladder climbing were considered. Due to a limited number of studies pertaining to these areas, ladder-climbing studies conducted with non-industry-based participants were also included.

1.2.2 Phenomena of interest

Studies that evaluated the musculoskeletal, physiological and other physical health risks to WT (both onshore and offshore) and others associated with repeated climbing of vertical ladders.

1.2.3 Types of studies

The review considered quantitative studies, which were either analytical or descriptive epidemiological study designs, or case control studies. In addition, qualitative studies were considered.

1.2.4 Types of outcomes

The physiological and biomechanical examinations of climbing were considered. In particular studies relating to force, electromyography (EMG) joint range of motion studies from a biomechanical perspective, and studies relating to oxygen consumption ($\dot{V}O_2$), energy expenditure and grip strength from a physiological perspective were considered.

1.2.5 Search strategies

The review sought studies in English and searched thirteen databases. The following databases were searched: SpringerLink, Web of Science, Web of Knowledge, Scopus, PubMed, Mendeley, Directory of Open Access Journals, Google, Google Scholar, Academic Search, JSTOR: Journal Storage, Medline, IEEE Xplore.

1.3 RESULTS

1.3.1 Overview

Thirty-four relevant journal papers were found. However, few studies were found that specifically related to the physiological analysis of WT. No studies were found that directly related to the biomechanical analysis of WT or the wind power industry. Specific occupational groups included in the studies reviewed were: coal miners (Gallagher *et al.* 2001); armed forces personnel (Pelham *et al.* 2006); fire fighters (Nuwayhid *et al.* 1993), offshore petroleum industry workers (Morken *et al.* 2007), and construction workers (Lipscomb *et al.* 2010). The remainder were either general population studies or descriptive studies using healthy participants.

1.3.2 Background

Earlier studies conducted on ladder ergometers investigated the $\dot{V}O_2$ at different ladder speeds with a view to evaluate how these compared to treadmill running and cycling (Kamon, 1970, Kamon and Pandolf, 1972 and Kamon *et al.* 1973). The first two of these studies investigated ladder climbing with pitches (*i.e.* a lean of the ladder from the horizontal plane) of 60 degrees (Kamon, 1970, Kamon and Pandolf, 1972), with the third at 80 degrees (Kamon *et al.* 1973). Although these studies were not conducted with the ladder climbing industry in mind, they do have relevance; the results of which are discussed in section 1.3.4. Since these studies over 40 years ago, only one piece of reported research (Barron *et al.* 2018) has been conducted on a vertical ladder ergometer (90 degree pitch). Currently available ladder ergometers, such as the H/P Cosmos discovery (Nubdorf, Germany) are pitched at 70 degrees 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 (e.g. Milligan, 2013; Vi, 2008) or on pitched ladder ergometers such as those used in the 1970s.

The experimental research into ladder climbing has focused on different parameters including: forces applied at the hands and feet, $\dot{V}O_2$ of climbing at different speeds, and the risk of falling. This review will examine each of these aspects with a particular focus on the ergonomic factors.

1.3.3 Biomechanical analysis

Bloswick and Chaffin (1990) investigated the biomechanical aspects of ladder climbing. The sample were not experienced climbers and included 10 male participants, two in five different age sectors (age range 18 to 44 years). The task for each participant consisted of 35 climbs up and down a static 7 rung ladder (climbing height = 2,7 m). Hand and foot forces and locations on the rungs, in conjunction with EMG data were measured, providing sufficient data to develop a biomechanical model of dynamic joint moments and back forces. The forces applied by the hands and feet changed as a function of time, with 9 % and 61 % of the variation respectively, explained by time (*i.e.* force application increase with time). The time, however, is not comparable to the wind turbine climbing, due to the repeated ascent and descent described above. From a forces perspective this study found that rung separation, climbing speed, and climbing direction were not important in that they explained only about 1 % of the variation in hand and foot forces. Anthropometric measurements explained 13 % of the torque generated on the rungs by the hands.

Further exploration of the data showed shorter, heavier participants to have significantly wider preferred hand and foot separation (39,9 cm and 28,2 cm, respectively) than the average (30,5 cm and 17,8 cm respectively) for the sample. Although the absolute values for the separation were specific to the population sample, the desired separation for shorter and heavier climbers was significantly greater than the rest of the population examined. The authors concluded that standard width ladders of 38,1 cm are suitable for all except participants who were both short and heavy, and suggested that low friction between the rungs and the feet may cause forward slipping of the foot, based on analysis of horizontal and vertical forces. However, this conclusion was based on just the kinetics of climbing and did not simulate slipping.

Armstrong *et al.* (2009) similarly investigated the biomechanical aspects of fixed ladder climbing, particularly force application. This included different climbing strategies, ladder pitch and the influence of carrying an external toolbox. The study had 12 non-ladder climbers (n = 6 males, n = 6 females, mean (standard deviation (SD)) age – 21 (2) years). Each participant was asked to climb a fixed vertical ladder using one of two techniques; grasping ladder rungs or side rails. Each participant only performed the climb three times at a self-selected pace. There was a pause at the top of the climb, and again before beginning the next climb. When ascending and descending, greater forces acted on the feet (105,7 % and 97 % bodyweight) than hands (34 % to 36 % body weight) suggesting most work is done by the lower extremities. Peak forces on the hands were greater using the rungs (34 % [ascent] and 36 % [descent] body weight) compared to the side rails (29 % body weight [both ascent and descent]) and increased for both techniques when participants climbed with a toolbox (42 % to 44 % body weight). Hand placement during rung climbing was constrained by rung spacing, while hand placement during rail climbing was determined by climber preference. It was shown that required hand force is related to vertical hand placement and body centre of mass position in both rung and rail conditions. Lateral hand forces (forces pulling the body left and right) may tend to destabilise the climber from the centre of the ladder. This occurs when hand placement on the ladder is not directly above the shoulder of the climber.

During this study the ladder was tilted forward (10 degrees) and laterally (5 degrees). Tilting forward reduced hand forces, which is consistent with the biomechanics of climbing and with previous studies. Tilting the ladder laterally did not significantly affect peak hand and foot forces, but it did affect the observed load/unload cycle time for hand and foot climbing movements. This indicates that the participants climbed more slowly on the laterally tilted ladder. The participants also reported that they found it much more difficult to climb a laterally tilted ladder than a vertical ladder. While acknowledging these useful insights, it must be kept in mind that: the ladder was only 3,05 m (10 feet) long, involving five steps up, five steps down; the participants were non-ladder climbers; participants only performed the climb three times. Armstrong *et al.* (2009) highlighted that carrying a toolbox increased peak forces acting on the hands (2 % body weight for rungs and 13 % bodyweight for rails) and increased variability in peak hand forces. It was reported by the participants that a 10 degree incline in the ladder made it much easier to carry the toolbox. While the precise means of carrying the toolbox was not specified, it was highlighted by the authors that workers should never be allowed to carry equipment or tools up or down a ladder with one hand. While this incurs the obvious safety risk of having to maintain balance with one hand, the biomechanical consequences of the addition of balance and loading increase peak forces and leads to inter- and intra-participant variations in climbing style. Force transducer data demonstrated mean peak hand force on the rungs for climbing was slightly greater than the 30 % determined by Bloswick and Chaffin (1990). It is very close to the 36 % value reported by Ayoub and Bakken (1978). They reported that although significant inter- and intra-participant climbing styles were observed for rung and rail climbing, it was still possible to conclude that most of the work was performed with the lower limbs, whilst the hands must constantly exert force to prevent falling from a vertical ladder.

In summary, from these particular studies, the feet are the primary load-bearing interface during ladder climbing, while the hands are largely responsible for balancing the body during climbing and for recovery after a slip or trip. The hands are used to grasp the rungs and prevent falling before the feet react. Holding the rails instead of the rungs does result in lower hand forces but increases the instability of the body. Foot forces measured during climbing have varied between 55 % (Bloswick and Chaffin 1990) and 96 % (Armstrong *et al.* 2009) of a climber's bodyweight. This force increases as time into the climb increases indicating greater acceleration of the limbs with less control.

1.3.4 Physiological analysis

Ladder climbing is a generic task that is common in a number of occupations. However, there is only limited literature available that details the physiological demands of ladder climbing. Gledhill and Jamnik (1992) reported that the metabolic requirements of fire fighters ascending a ladder for 2 minutes 57 seconds, required a mean (SEM) $\dot{V}O_2$ of 30,6 (0,3) $mL.kg^{-1}.min^{-1}$ and a mean (SEM) HR of 166 (10) $b.min^{-1}$. Only eight participants were tested; neither the rate at which they climbed the ladder nor the rung distance was reported. It is assumed that 22 kg of personal protective equipment (PPE) and self-contained breathing apparatus were worn.

Milligan (2013) assessed the physiological demand of forty two non-trained ladder climbers to ascend and descend a static 10 rung vertical ladder (total ladder height = 3 m), continuously for 3 minutes, at three speeds. The resultant mean (SD) $\dot{V}O_2$ equated to 18,8 (2,2) $mL.kg^{-1}.min^{-1}$ at the slowest speed of 17 $rungs.min^{-1}$ increasing linearly to 23,6 (2,8) $mL.kg^{-1}.min^{-1}$ at 24 $rungs.min^{-1}$ and 28,9 (3,4) $mL.kg^{-1}.min^{-1}$ at 34,5 $rungs.min^{-1}$. Mean (SD) HR was reported to be 144 (18,6) $b.min^{-1}$ at 17 $rungs.min^{-1}$, 135 (22,6) $b.min^{-1}$ at 24 $rungs.min^{-1}$ and 147 (19,7) $b.min^{-1}$ at 34,5 $rungs.min^{-1}$. Maximum grip strength was measured before and immediately after ladder climbing in fourteen individuals, the data showed decrements in maximum grip strength of 17,8 % (left hand) and 15,5 % (right hand) when ascending and descending a ladder at 34,5 $rungs.min^{-1}$. These are close to the values reported in previous research in which decrements in maximum grip strength of 20 % following a stretcher-carrying task resulted in poorer performance of fine motor skills (Leyk *et al.* 2006). These performance decrements were not observed when maximum grip strength was reported to be reduced by 12 % or less (Leyk *et al.* 2006). Thus, ladder-climbing at 17 $rungs.min^{-1}$ or 24 $rungs.min^{-1}$ would not be predicted to impair performance of subsequent fine motor control tasks. Participants reported 24 $rungs.min^{-1}$, to be the most comfortable climbing speed compared to 17 $rungs.min^{-1}$ which was reported to be uncomfortably slow, and 34 $rungs.min^{-1}$ to be uncomfortably fast. This suggests that 24 $rungs.min^{-1}$ is the optimal minimum rate to ascend and descend a ladder. However, it should be noted that these data are based on non-trained climbers, over short distances of combined ascend and descent.

Vi (2008) conducted a study examining the physiological differences between a pitched and a vertical ladder. The difference in energy expenditure and HR when repeatedly ascending and descending a 6,1 m height on both a vertical ladder (90 degrees) and a ladder pitched at 75 degrees was investigated. Participants were required to climb for at least 5 min at a rate, which elicited a HR response of either greater than 90 $b.min^{-1}$ 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^{-1} v. 13,1 kcal.min^{-1}) and mean HR (142 b.min^{1} v. 155 b.min^{-1}) when climbing at 75 degrees and 90 degrees respectively.

The use of short ladders, which require the participants to repeatedly ascend and descend, have been shown to reduce the physical demand when compared to ascending alone. Milligan (2013) suggested that the use of short ladders for physiological testing of ladder climbing fails 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 (Kamon, 1970). Whilst Kamon (1970) found a 26 % decrease in $\dot{V}O_2$ when descending a ladder ergometer compared to ascending, the recent work of Barron *et al.* (2018) observed a much greater decrease of 46 % (mean (SD) 28,3 (3,5) mL.kg^{-1}.min^{-1} to 15,3 (3,7) mL.kg^{-1}.min^{-1}) in $\dot{V}O_2$ when ascending compared to descending a 30 m vertical ladder. The climb took place inside a wind turbine guided by a metronome at 24 rungs.min^{-1}. Rung spacing was 28 cm and mean total climb time was 3 min 45 sec. It must be acknowledged that the study by Barron *et al.* (2018) required only a single ascent and descent of the 30 m vertical ladder.

In summary, the limited data available demonstrate a significant physiological demand both aerobically and in terms of local muscular fatigue (grip strength) associated with ladder climbing. There is a possibility that the decrements in grip strength observed during ladder climbing could impact on technicians' ability to perform subsequent manual handling tasks; this warrants further investigation. However, care must be taken when analysing these results as the data yielded from the extant literature cannot be generalised to long ladders typically used in wind and offshore energy applications. Either because existing research involved short ladders, mandating alternating ascent and descent cycles, or because of the non-vertical pitch, which lowers the energy cost (Vi, 2008) and alters then fatigue profile. 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.

1.3.5 Musculoskeletal injury and disorders

Ladder falls are the leading cause of fatal falls (BLS, 2012) with 63 % of ladder injuries resulting in a fracture or sprain (Partridge *et al.* 1998). Nearly half of these ladder fall fractures result in medical cost per case of over $5000 (Smith *et al.* 2006). However, these severe injuries are believed to be preventable through safer ladder climbing practices (Muir and Kanwar, 1993; Socias *et al.* 2014). Identifying the climbing practices associated with reduced fall risk, and the individuals at risk for falling, is important to develop and target strategies for reducing the number of people who suffer injuries from ladder falls. The majority of falls from ladders result from a climber's overbalance, slip or misstep (Shepherd *et al.* 2006).

Much of the ladder-related literature has emphasised the prevention of injury, particularly in relation to slipping. A recent series of studies by Pliner and colleagues has examined the effects of climbing conditions on slip likelihood (Pliner *et al.* 2014, Pliner *et al.* 2015, Pliner and Beschomer 2017, Pliner *et al.* 2017). This series of studies examined the incidence of falls from ladders, the causes of falls, and the resulting implications. The authors suggest that current guidelines recommend 'proper' ladder climbing to avoid a ladder fall, but there is a lack of understanding on safe ladder climbing biomechanics. The first of these studies (Pliner *et al.* 2014) examined 32 males (frequent ladder users) from three age groups (18–24, 25–44 and 45–64 years) climbing with different foot positions (restricted toe clearance and unrestricted) and different hand positions (rungs and rails). A 3,66 m (12 ft) vertical ladder was climbed at a 'comfortable but urgent pace' eight times. They found that longer double stance time (both feet in contact with the rungs) and more variable foot and body positioning were leading causes of slips. Although intuitively a double stance time might seem like a more stable climbing position, the authors speculated that increased slipping resulted from increased time spent stabilising the body rather than climbing, and difficulty supporting their weight in order to apply the double contact. A larger double support time may indicate that participants slowed their climbing rate, fixing their weight on the rung resulting in fatigue in the limbs due to increased climbing times. The increased variability within climbing styles may lead to an increased risk of slips. Thus, improving technique through training may have potential for improving control and consistency and reducing slip risk.

Pliner *et al.* (2014) found that grasping ladder rails versus the rungs caused significant changes to the biomechanics of climbing and suggest it may influence the likelihood and recovery from slipping (preventing a fall). When using a ladder, climbers must choose between grasping the vertical rails of the ladder or the rungs of the ladder. A slip or misstep can manifest into a fall event if the hand decouples from the ladder. Some research, outlined above, has suggested that grasping the rungs may provide a better grip than grasping the rails and thus help prevent falls (Armstrong *et al.* 2009; Barnett and Poczynck 2000; Young *et al.* 2009). Other research suggests that hands may be more relevant to the recovery response after a slip has occurred, rather than contributing to the slip risk itself (Paul *et al.* 2013). For example, faster muscle response occurs when placing hands on the rungs compared to with the rail (Paul *et al.* 2013). Further, breakaway testing, where a handhold is forcibly pulled from the hand while the participant holds on with maximal effort, revealed that force generation capacity is higher when grasping horizontally-oriented rungs than when grasping vertically-oriented rails (Young *et al.* 2009). This research on hand position has been conducted with a view to reducing the risk of falling rather that improving climbing mechanics. Further research on hand positioning from a climbing technique perspective, to compliment the risk aversion research, is required for WT.

Although no minimum toe clearance space exists in the Wind Power industry, this aspect has been examined in other industries. In order to maintain a solid footing surface during ladder climbing, the US Mining Safety and Health Administration (MSHA) requires that ladders be placed at least 76 mm away from other surfaces, while the US Occupational Safety and Health Administration (OSHA) requires a 180 mm clearance. These conflicting toe clearance rules suggest that an understanding of the effects of restricted toe clearance on slip risk is needed to assess the appropriateness of the different guidelines. Pliner *et al.* (2014) reported that maintaining sufficient toe clearance and targeting ladder safety training to younger and older workers may reduce ladder falls, however, no value was placed on what constitutes a minimum acceptable requirement for toe clearance.

Toe clearance restriction, which constrains foot placement, had a strong effect on slip outcome. Slipping was six times more likely ($p < 0{,}01$) with restricted toe clearance than with unrestricted. The maximum toe clearance observed in the unrestricted condition was less than the minimum requirement for OSHA (180 mm). This suggests that the OSHA rule exposes workers to significantly less risk than the MSHA rule (Pliner *et al.* 2014). Although studies such as Pliner *et al.* (2014) have mentioned the use of toe clearance as a factor influencing falls, no experimental studies have been carried out linking a minimum toe clearance to an increased level of falling. The absence of evidence, and conflicting toe clearance regulations suggest there is a need to understand the effects of restricted toe clearance on slip risk in order to recommend appropriate guidelines. The data from Pliner *et al.* (2014) has identified safer ladder climbing techniques such as holding the rungs rather than the rails and having a minimum toe clearance of 160 mm.

Pliner *et al.* (2014) reported that both younger (age 18–24) and older (age 45–64) age groups had a significantly greater number of slips than the middle age group (age 25–44). The younger group had the greatest slip risk. To further explore the age factor, the authors propose future research that quantifies which factors related to age (experience, strength, reaction time, body mass) are most relevant to slipping and may provide insight into the underlying causes by which age influences slip risk.

In addition to the work of Pliner *et al.* (2014), ladder design and the biomechanics of ladder climbing have been found to be associated with slip propensity and a climber's ability to recover from a slip (Schnorenberg *et al.* 2015). Schnorenberg *et al.* (2015) examined the factors that contribute to falls from ladders and specifically those that influence the motor response (muscle activation onset and peak activity timing) from ladder falls. This study expanded on the previous study by Pliner *et al.* (2014), with the inclusion of EMG to examine the effects of hand placement (rung versus rail) on muscle activation onset and peak activity timing in response to slipping on a ladder and to sequence the timing of events following slip initiation. 11 experienced ladder climbers (7 males, 4 females; age range 18 to 61 years) were examined climbing a 12 rung ladder (total length = 3,6 m) a total of six times. One of the rungs had a release clasp allowing the experimenter to release it causing a slip. Data analysed were EMG onset time and peak activity time from five bilateral muscles (semitendinosis, vastus lateralis, triceps, biceps and anterior deltoid).

Schnorenberg *et al.* (2015) showed significantly slower muscle activation onset and peak response times occurred during rail hand placement, suggesting that grasping ladder rungs rather than rails may be preferable for improving the speed of the motor response (the muscle activation following a slip). Muscle onset times were on average 39 % (280 ms) faster when grasping the rungs compared to the rails. The faster response experienced while grasping the rungs may be because the motor system was already cued to execute a grasping response while holding on to the rungs, whereas a change in grasping strategy was required when grasping the rails. Grasping the rails may require climbers to switch their grip strategy following the perturbation. Regardless of the mechanism that caused it, the delay of 280 ms is significant. For example, a reduction in postural response of just 280 ms after an agility training programme was associated with a 40 % reduction in fall events in stroke patients (Marigold *et al.* 2005). The triceps muscle activated and reached peak activity earlier after the slip, indicating that subjects may initially extend their arms prior to generating hand forces. The study also revealed that slips tended to occur around the time that a foot and hand were in motion and there were just two points of contact (one hand and the slipping foot).

Two recent studies support these findings. The first (Pliner and Beschorner, 2017) investigated the effects of different temporal (2-beat, 4-beat) and coordination (lateral, diagonal) ladder climbing patterns on fall severity. The two temporal patterns used were 2 beat (upper and lower limb moving in unison) and 4 beat (movement of each limb is staggered). The two coordination patterns of the limbs with overlapping airbourne phases were lateral (ipsilateral limbs moving together) and diagonal (contralateral limbs moving together). They did not find that climbing patterns affected fall severity. They concluded that despite previous studies (e.g. Hammer and Schmalz 1977) suggesting that certain climbing patterns are safer, they could not suggest a specific climbing pattern to improve recovery with a ladder after a perturbation (use of a step that slipped away from under the participant). The second study (Pliner *et al.* 2017), studied thirty-five participants (n = 22 males; n = 13 females) to examine the recovery of participants following a perturbation. Each participant experienced six unexpected ladder missteps, for three glove conditions (bare hands, high friction, and low friction) and two climbing directions (ascent, descent). Fall severity (whether the participant could get back on the ladder or fell away to a fall arrest harness) was increased during ladder descent ($p < 0,001$), with gloves not affecting fall severity. Thus, additional protection in the form of a fall arrest harness may be needed when descending a ladder.

Pliner *et al* (2017) compared males and females and concluded that females may benefit from targeted interventions like training. When assessing the ability to recover from a slip, the ability of males remained consistent with no learning effect apparent. However, the ability of females to recover from a slip improved with increasing trials. The finding indicates that female participants who have been exposed to one, but not many ladder perturbations may be at increased risk of falling. Sex differences such as upper body strength (Muir and Kanwar 1993) and anthropometry (Chaffin *et al.* 1999) may explain why this effect was only seen in females and not males. Although a correlation between upper body strength and slips was not explicitly tested for in the study, reduced strength and stature may have forced the females to 'fine tune' their strategy as opposed to relying in their strength and height. Male participants were taller than females on average ($p < 0,01$) which may have allowed male participants to reach higher for rungs or extend lower to re-establish foot placement onto the rungs after a misstep. Further research should examine if this gender difference holds true for shorter lighter males to establish if it is a gender factor or a weight/height factor. Finally, this study does not suggest that gloves are effective for preventing ladder falls; thus, interventions involving gloves may be of limited effectiveness.

Epidemiology research has suggested that climbing direction (ascent/descent) may be an important risk factor for falls from ladders. A review of mining injury reports reveals that ladder fall injuries occur three times more often for miners exiting (and thus descending ladders) mining equipment compared with entering equipment (Moore *et al.* 2009). One explanation that was offered by the authors of this study is that miners may have poorer balance during descent due to the amount of vibration exposure that is experienced between ascent at the start of a shift and descent at the end of the shift (Moore *et al.* 2009). However, previous research has suggested that exposure to vibration does not have substantial short-term impacts on balance (Cornelius *et al.* 1994; Santos *et al.* 2008). An alternative hypothesis is that more falls are experienced during ladder descent because recovering from a perturbation during descent is more challenging than during ascent due to the body's downward momentum. Although injury records show more descending ladder falls than ascending, a gap in the literature exists regarding whether this is because of some intervention (e.g. fatigue) that occurs between ascent and descent, or because recovering from a perturbation during descent is more challenging. Moore *et al.* (2009) identified the effects of foot positioning, hand positioning and ascent or descent on slip outcomes in order to better inform safer climbing. To date no controlled study has been performed to consider the effect of ascent or descent on slip risk (as opposed to outcome).

In summary, the combined results suggest that ladders with unrestricted toe clearance (in the form of space behind the climber) and ladder climbing training programmes, particularly for females and younger and older workers, may reduce ladder slipping risk.

1.3.6 Influence of carrying load

Armstrong *et al.* (2007) undertook a research study to examine coal miners who often handle heavy electrical power cables, weighing up to 10 kg per meter in confined spaces. These cables are manually lifted and attached to the mine roof to prevent damage from mobile underground equipment. Data suggest that workers who commonly perform cable-handling tasks experience a high rate of lost-time due to back injuries. In this study, six male underground miners performed a total of 12 cable-hanging tasks in standing, stooping, and kneeling postures, during which kinematic and ground reaction force data were collected.

Reductions in vertical workspace were found to result in a linear increase in the peak moment experienced by the lumbar spine ($p < 0,05$). In restricted postures, peak moments were not significantly different in stooping or kneeling postures ($p > 0,05$). Average lumbopelvic flexion during the tasks was highest in stooping conditions, followed by standing and kneeling exertions ($p < 0,05$). Further research, specifically detailing the equipment (weight, size, frequency of carries and duration of carries) carried into the nacelle should be considered in order to obtain implications for wind turbine technicians.

In summary, the outcome of repeated ladder climbing and confined space working in terms of injuries, accidents and musculoskeletal disorders (MSDs) such as back pain (Armstrong *et al.*, 2007) developed as a result of ladder climbing/confined space working is relatively under-researched.

1.3.7 Climbing style/technique

In addition to the research outlined earlier regarding 2 beat or 4 beat temporal climbing (Schorenburg *et al.* 2015), it has been shown that 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). This assessment of technique requires further study with a specific focus on kinematic interactions with the ladder, and examining how the kinematics of climbing change over the duration of the climb. It is recommended (Health and Safety Executive [HSE], 2014), that three points of contact are kept with the ladder at all times. In practice, this may not be the case.

1.3.8 Rest breaks

The effects of rest breaks on climbing performance have only been assessed in one study. Arlinghaus *et al.* (2012) provided evidence for rest breaks protecting against ladder fall injuries. They identified 629 workers who had experienced a work-related ladder-fall, and interviewed 306 of them using a standardised questionnaire about the circumstances surrounding the injury. Survival analyses were used to estimate time to injury, and hazard ratios (HaR) for time to injury, were compared between workers who reported no rest break (reference) and workers who reported rest break(s) prior to the injury (accumulated break time categorized into 0, 1–15, 16–30, and >30 minutes). They found a clear dose-response relationship indicating that longer accumulated break time was associated with a significantly longer time to injury when compared to workers without rest breaks (total break time 1–15 minutes: HaR 0,60, 95 % confidence interval (95 % CI) 0,44–0,83; 16–30 minutes: HaR 0,50, 95 % CI 0,33–0,75; >30 minutes: HaR 0,34, 95 % CI 0,23–0,51). From these results, they concluded that the longer rest break allowed for a prolonged period of work time spent without an injury. These findings suggest that rest break design could be used as a tool to enhance fatigue management and workplace safety.

A further factor for WT is that the nature of manual ascent or descent of turbines on multiple occasions, back to back, might constrain the timing of rest breaks. It can be recommended that the timing and duration of rest breaks within a climb is examined. Beyond what Arlinghaus *et al.* (2012) suggest, further research is warranted on the interaction between the timing and duration of rest breaks and job performance, physical and mental fatigue and musculoskeletal disorders.

1.3.9 Ladder pitch

As illustrated throughout the studies reviewed, the pitch of the ladder used has not been consistent. Although research on physiological demand has been conducted on short vertical ladders (e.g. Milligan 2013), pitched ladders (e.g. Bloswick and Chaffin, 1990) and ladder ergometer climbing at 60 degrees over short time periods (e.g. Kamon 1970) this is not generally applicable to the Wind Power industry or similar industries which require individuals to climb long and vertical ladders. Recent research by Barron *et al.* (2018) studied nine male participants climbing a ladder ergometer at 75 degrees and subsequently at 90 degrees, adjusted for an equivalent vertical climb rate. Each participant completed three climbing bouts at different vertical speeds. The study assessed whether modifying the pitch of a 75 degrees ladder ergometer to vertical had a cardiorespiratory or psychophysical effect on climbing. Each participant was monitored for heart rate (HR), $\dot{V}O_2$ and rating of perceived exertion. They found that vertical climbing induced higher $\dot{V}O_2$ (mean increase 17,3 %), higher HR (mean increase 15,8 %), and higher rating of perceived exertion at all speeds, and that moving from 75 degrees 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. Leaning forward onto a 75° ladder allow the centre of mass to move over the base of support at the feet, making the task easier. This corresponds with the data of Vi (2008) who found reduced energy expenditure when climbing at 75 degrees compared to 90 degrees (see section 1.3.4). In summary, consideration should be given to installing ladders at a pitch of 75 degrees or lower to reduce energy expenditure for climbers, where possible.

1.4 DISCUSSION

This literature review has outlined ladder climbing studies from a range of industries. This research has mainly been aimed at understanding forces applied at both hands and feet, climbing forces 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 the physiological demands of ladder climbing (Kamon 1970; Kamon and Pandolf 1972, Gledhill and Jamnik 1992; Vi 2008; Milligan 2013; Barron *et al.* 2018).

From a biomechanical perspective, climbing technique have not been sufficiently addressed. One paper has shown that 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). A more recent paper (Schorenburg *et al.* 2015) has shown that climbing style does not impact on fall severity after slipping. Notwithstanding these two studies, there is no further information to guide limb movements. This assessment of technique requires further study. Grip strength pre and post climbing was only assessed in one study (Milligan 2013). This has primarily been due to the limited duration of the climbs tested with grip strength showing no differences in short climbs. It is suggested that longer duration climbing (80 m to 120 m) will have an impact on grip strength and requires further examination. Although research on the physiological demands has been conducted on short ladders, pitched ladders and ladder ergometers climbing at 60 degrees over short time periods, this is not generally applicable to the Wind Power industry or similar industries which require individuals to climb long and vertical ladders.

1.5 CONCLUSION

All of the research examined has focussed on non-WT. Many of the papers reviewed were from construction, extraction (mining) and installation/maintenance sectors and in jobs which might be expected to emulate some of the physical aspects of the work of WT. While some recommendations such as holding the rungs instead of the rails remain relevant, the importance of this beyond 30 m is unclear. The ecological relevance of the ladder climbing literature is limited as ladder climbing research has been conducted either on short ladders involving multiple ascents and descent or, alternatively, using a non-vertical ladder.

It is concluded that there is a lack of literature on the specific ergonomic risks associated with working in the Wind Power industry. As this sector is relatively young, longitudinal research around this occupational group is limited, with most literature on ladder climbing focusing on healthy populations or construction and mining industry employees. In relation to the specific review objective to assess previous ergonomic assessments performed on ladder climbing, the short nature of previous assessments on ladder climbing makes it extremely difficult to generalise findings to WT.

2 TASK ANALYSIS

2.1 OBJECTIVE

To determine whether the current industry physical fitness standards are adequate to assess a technician's ability to undertake the expected level of ladder climbing.

2.2 INTRODUCTION

In order to determine whether an industry has the appropriate physical fitness standard (Physical Employment Standards [PES]), it is important to understand the methodological approach to developing a legally defensible PES. In the UK, tasked-based PES have been introduced by the Military (Rayson and Holliman, 1995; Rayson *et al.* 2000a; Allsopp *et al.* 2003); Fire and Rescue Service (Siddall, 2014); Maritime and Coastguard Agency (Milligan 2013); Royal National Lifeboat Institution (Reilly *et al.* 2006a; Reilly *et al.* 2006b; Reilly, 2007), and recommended to the Oil and Gas Industry (Energy Institute, 2012). These standards generally base the suitability for employment on the physical and physiological components associated with the safe and successful completion of tasks that are considered generic and critical, for a specific job, thus guaranteeing employment is free from age and sex discrimination. Ensuring that individuals are capable of performing the job, by means of a PES, can lead to an increased quality and quantity of work, reduce injuries and absenteeism and subsequently improve employee lifestyle (Klein *et al.* 1986; Anderson, 1981; Rayson, 2000b). Thus, the reasons for introducing a PES into the workplace are to:

– Minimise the potential for employing physically unfit individuals in physically demanding jobs; this can be costly, both in human and economic terms (Rodgers, 1988; Hodgdon and Jackson, 2000).
– Ensure that an employee is physically capable of completing the critical tasks of a job to at least the minimum acceptable standard, and provide employees and potential employees with a target to reach and sustain (Reilly, 2007).
– Decrease the potential for injury, thereby providing a 'duty of care' for all employees (Rodgers, 1988).
– Ensure selection is based solely on ability to complete critical tasks and is therefore fair and unbiased towards age or sex (Reilly, 2007).
– Base retirement on capability rather than an arbitrary age (Davis and Dotson, 1987).
– Provide feedback on rehabilitation and return to work (Anderson, 1981; Rayson, 2000b).
– Encourage self-training, self-evaluation and a healthier lifestyle (Anderson, 1981; Rayson, 2000b).
– Increase confidence of individuals and teams (Rayson, 2000b; Shephard and Bonneau, 2002).

By setting a valid minimum PES, employers should maximise the number of employees who are able to complete critical tasks. If the standards are too low, employers will increasingly recruit individuals who are incapable of meeting the job demands. If they are too high, a proportion of individuals will be rejected who would have been capable of doing the job

(Biddle and Shepherd-Sill, 1999). Therefore, a minimum standard should select, as accurately as possible, individuals who can perform the critical tasks of a job to at least to the minimum requirement.

To be valid and legally defensible a PES should be based on the most common (generic) and critical physically demanding tasks that are crucial for operational performance of the job (Tipton *et al.* 2013; Milligan *et al.* 2016). These tasks are identified by evaluating an occupation to determine the frequency, importance and nature of the tasks involved (Greenberg and Berger, 1983; Anderson *et al.* 2001; Taylor and Groeller, 2003; Gumieniak *et al.* 2011). Thus, PES can include measures of strength, endurance, anthropometrics, flexibility, motor skills and cardiovascular and metabolic fitness (Stevenson *et al.* 1992; Rayson *et al.* 2000a; Anderson *et al.* 2001; Allsopp *et al.* 2003; Reilly *et al.* 2006a; Reilly *et al.* 2006b; Reilly, 2007; Jamnik *et al.* 2010 Milligan 2013).

Several authors have recommended templates for developing and validating job specific physical fitness protocols and performance standards as *bona fide* occupational requirements (Chahal *et al.* 1992; Taylor and Groeller, 2003; Gumieniak *et al.* 2011; Tipton *et al.* 2013). These include:

– Justifying the need for such a standard.
– Forming a project management team.
– Job familiarisation, including the review of professional manuals, reports and interviewing subject-matter experts.
– Task analysis
– Analysing a representative subset of the physically demanding tasks
– Characterisation of the tasks (simulated).
– Development of a test protocol, which comprises either a job simulation, related fitness component, or combination thereof.
– Standardisation of test protocol/s.
– Establishing the scientific accuracy of the test/s.
– Development of a performance standard.
– Implementation of the standard.
– Ongoing review of a standard to accommodate the changing workforce and work demands.

Thus, a PES should be based on the most physically demanding tasks of an occupation and be designed to reflect both the physiological and physical components of the task. It should not be based upon other factors such as age or sex.

Accordingly, the following requirements are considered to be fundamental to the establishment of a valid PES (Tipton *et al.* 2013):

– <u>*Task analysis*</u> – Review the components of the job requiring a significant physical fitness component, and determine the importance of these tasks to identify those which are critical, (common and/or essential tasks) for the successful completion of the job.
– <u>*Establish the method of best practice (MOBP)*</u> – Determine the MOBP to undertake each task.
– <u>*Agree an acceptable minimum level of performance*</u> – Establish the minimum level of performance on the critical tasks when performed using the MOBP as sanctioned by the employer.

– *Task quantification* – Establish the physical and physiological demands associated with the critical tasks and decide upon the most appropriate descriptive statistical measure (e.g. the minimum, maximum, mean, percentile, mode, median *etc.*) to maximise employability, without sacrificing the ability to perform the critical task.
– *Determine the safe relative workload* – e.g. the percentage of an individual's maximum work capacity it is reasonable to expect them to work at.
– *Designing a PES* – Establish the appropriate selection criterion and design a simple-to-administer minimum PES.
– *Validation of the PES* – Validate the work undertaken.

In this section, the critical task analysis undertaken of ladder climbing and other tasks performed by WT are reported. In addition, the current fitness tests prescribed for WT are reviewed to determine whether they are valid and legally defensible.

2.3 METHODS:

2.3.1 Task analysis

In order to determine the physiological and biomechanical demands of climbing a ladder a thorough understanding of the task in terms of climbing speed, duration, rest breaks, clothing ensembles, environmental conditions and MOBP for performing the task were established. To further understand the role of a WT all physically demanding tasks, in addition to ladder climbing, were determined. The task analysis was completed by: observations of WT performing tasks; the research team undertaking tasks; reviewing operational manuals; using a focus group with an expert panel. The expert panel comprised of nine members of the offshore wind industry, who all have various experiences and job roles. Each Subject Matter Expert (SME) fulfilled at least one of the criteria detailed below; the expert panel covered all criteria.

1. Experience performing the task onshore
2. Experience performing the task offshore
3. Experience performing the task during an emergency situation
4. Experience in a position of leadership where you have directed other employees to perform the task and have observed the task being performed
5. Have witnessed the task being performed in an acceptable manner
6. Have witnessed the task being performed unsuccessfully and can attest to the reasons for, and the consequences of, this failure (e.g. A person was not fit enough to climb the ladder)
7. Witnessed and/or performing the task using several techniques and can comment on the advantages and disadvantages of these techniques

The results of the critical task analysis of the demands of ladder climbing were sent to the G+ committee for comment and endorsement.

2.3.2 Review of current physical employment standards for offshore wind technicians

Five companies from G+ responded to an email enquiry asking if any internal fitness standards/tests were implemented within their organisation. Companies were asked: What these tests are? What are the pass scores? Where these data came from?

2.4 RESULTS

2.4.1 Critical task analysis

The critical tasks were established by SME (Table 2.4.1) at meetings held on 13th, 18th and 19th September 2017.

Table 2.4.1: Demographics of the nine Subject Matter Experts (SME)

Job Title	Years in the industry	Years working as a technician	Age	Sex
Head of HSSE Offshore Technologies and Wind Construction	20	n/a	47	Male
Shift manager	8	4	44	Male
Site technician wind power	4,5	4,5	23	Female
SHE Advisor Wind Generation	6	–	51	Female
Vessel Master	8	–	50	Male
Offshore operational engineer	4	4	32	Female
QHSE Safety Advisor	8	–	45	Male
Senior Technician	7	7	43	Male
Authorising Officer	7	5	36	Male

The critical tasks are described below and include the most physically demanding activities associated with three groups of WT:

- 'Service Teams' – common for teams to be made up of three technicians (range 2 to 4), of which one will be a Team Leader.
- Troubleshooting Teams – likely to be two technicians.
- Balance of Plant Technicians – also known in some organisations as Operations Technicians.

The following task analysis is split into:

- Transfer from the vessel onto the turbine
- Ascent of the tower
- Descent of the tower
- Other physically demanding tasks
- Balance of Plant Technicians
- Emergency response procedures.

The terminology used throughout the critical tasks will be based on the Figure 2.4.1.
It should be noted that this analysis only applies to WT during operation. It does not include construction of the turbines or the other employees associated with construction and operation e.g. vessel crew, construction workers, survey workers and divers.

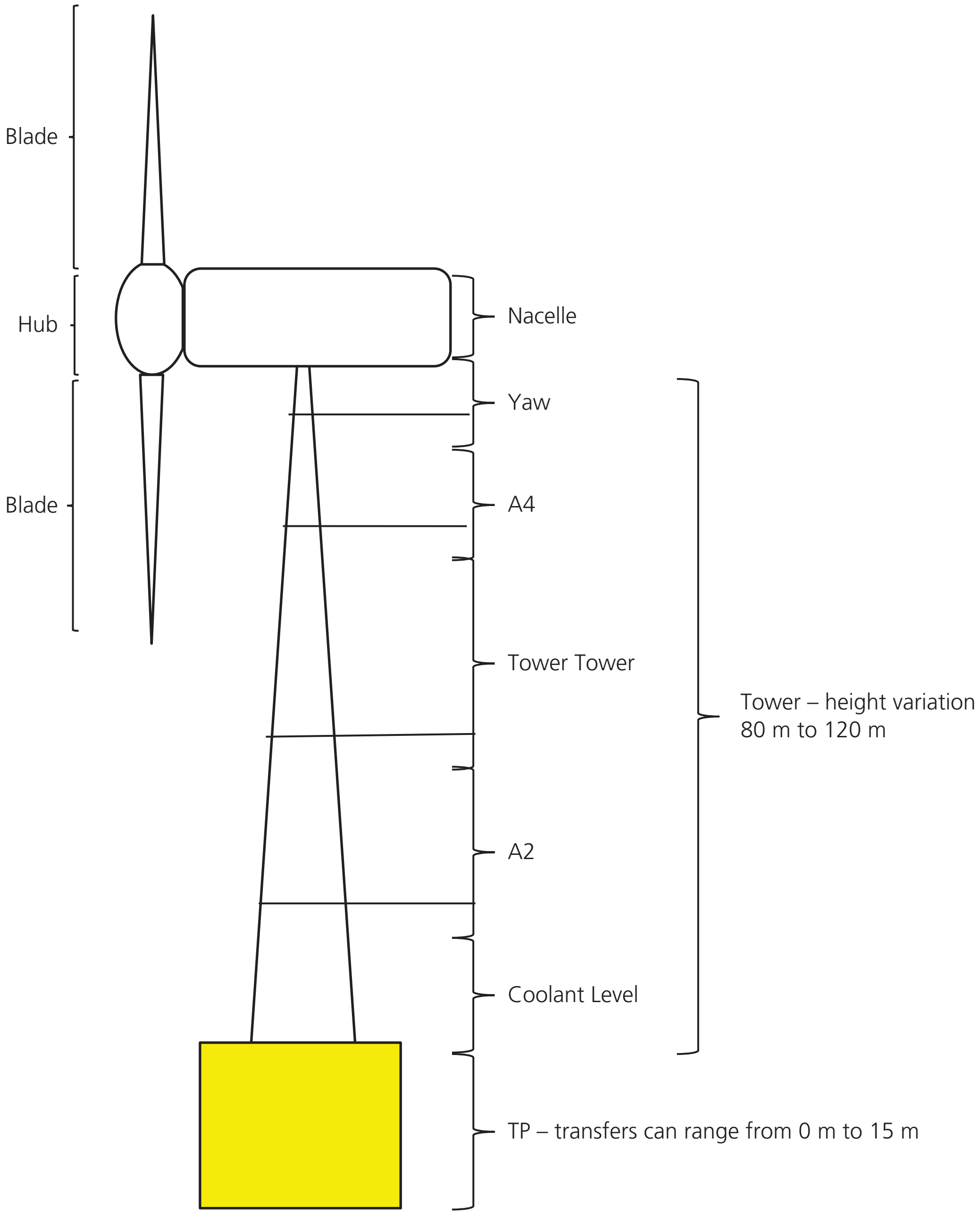


Figure 2.4.1: Schematic of an offshore wind turbine. The schematic is not to scale with variations occurring in all aspects across the industry. The model is based on a 3.6 Offshore Turbine

An overview of the shift patterns and the working day

The majority of operational servicing and maintenance work is carried out March to September, with a reduced number of WT working during the winter months of October to February. The experienced climbers amongst the SME reported that they were notably fitter by the end of the summer period, finding the same critical tasks much more physically demanding during the first quarter of the season. This suggests that WT gain fitness and/or become more efficient climbers as a result of repeated climbs. Thus, it would be worthwhile documenting this change in performance to see if it corresponds with incidences of injury, musculoskeletal disorders, slip, trips and falls and sick days taken.

A number of different shift patterns are implemented across the industry (Table 2.4.2). During these shift patterns 'bad weather days' could mean WT go through periods of not working. Some organisations automatically stand WT down after 9 days of continuous work and WT can stand themselves down if feeling excessively fatigued.

Table 2.4.2: Example shift patterns provided by the Subject Matter Experts

Shift Pattern		Employee Type
Days On	**Days off**	
4	4	Organisation based e.g. SSE
6	3	Site based
14	7	Travelling WT
7	7	Various
14	14	Those WT living on board a vessel – deep water fields

In many locations the time the working day starts is tide dependant and varies throughout the shift pattern, e.g. departure time may vary between 0300 and 1500. In general all WT work a 12 hour day. Either the day can be spent on one turbine or changing between turbines, (it was suggested that this would be up to three transfers, and only on rare occasions more). Further consideration could be given to optimal shift patterns based on cumulative physical and mental fatigue and restraints such as working start and finish times.

Transfer from the vessel onto the turbine
The time taken to transfer between the port and turbine can vary depending on the:

- Distance of the field from the port.
- Weather conditions.
- Sea state.
- The number of technicians aboard – this can be up to 12 (resulting in a potential of 3 drop offs before the final group is ready for transfer to the turbine).
- Sickness – if vomiting is reported a vessel will return to port.

Therefore, there is a potential for technicians to be in transfer for 3 to 4 hours.

All WT are required to transfer from the vessel to the TP via an external ladder (Figure 2.4.2). During 'trouble shooting' operations it is possible for WT to undertake approximately three jobs (this is constrained by the time it takes to transfer between turbines and the time taken to complete a job). During longer turbine services WT may only undertake one transfer. If multiple transfers are required it is often the deck hand and/or Skipper that may decide if the WT is capable of another transfer onto the turbine. Deck hands and Skippers will base this on the competence of the WT decent, reaction time of stepping back onto the vessel, and the time take to unclip from the fall arrest.

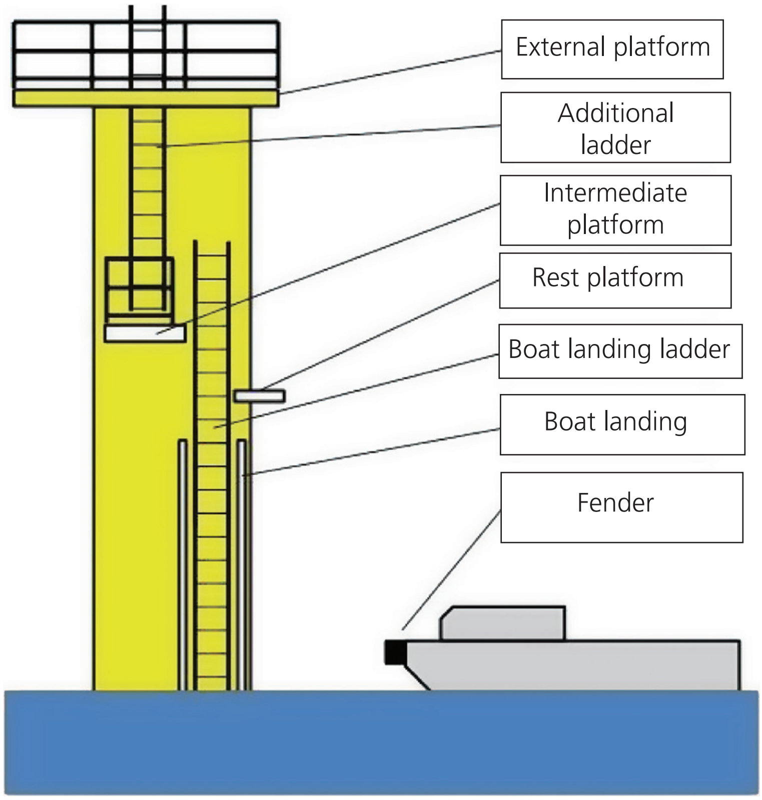


Figure 2.4.2: Schematic of a generic vessel transfer and ascent to the Transition Piece (Energy Institute, 2014)

Currently the external ladders are vertical, with the majority using a diamond shaped rung (each side = 4 cm) with a distance of 330 mm between rung mid-point to rung mid-point, 500 mm internal width and 680 mm external width. The design of external ladders is due to change on some new structures with external ladders being installed at a 7° lean, thus making ascent and descent technically different, but physically less demanding (please refer to section 1).

Prior to transferring onto the external ladder of the turbine WT need to don a lifejacket (approx. mass 2,3 kg), the appropriate PPE (minimum requirements – safety boots, gloves, glasses, climbing helmet (approx. mass 0,5 kg)), high visibility clothing, harness and attachments (approx. mass 6 kg). In cases where sea temperatures meet the companies set criteria (e.g. sea temperatures below 12 °C or 14 °C, and in some cases every transfer regardless of temperature), a sea survival suit (approx. mass 2,5 kg). It is worth noting that SME stated that most WT go from a resting/sleeping state to donning PPE and climbing in very short periods of time, without any physical preparation.

To transfer onto the turbine, WT will be connected to the fall arrest system and be required to step from the vessel onto the ladder. The make of turbine will determine the type of transfer, for some this may involve walking along a gangway onto the ladder, or stepping off straight onto the TP. Other transfers, where the vessel attaches to the external ladder, will be affected by sea state and thus the movement of the vessel will affect: the size of the initial step onto the ladder; the speed of transfer, and distance the WT will have to climb. This suggests a requirement for WT to be able to achieve hip flexion past 90°. SME indicated that the initial

5 m to 10 m of ascent following transfer were the fastest, but they were proceeded by a rest stage. The time taken for each WT to complete the initial climb onto the TP was estimated to be no more than 2 minutes. On reaching the top of the first ladder WT are often required to straddle the ladder opening (approx. 800 mm to 1000 mm) to transfer to either the intermediate external ladder or the external platform of the TP (Figure 2.4.2). On reaching the TP, the equipment and tools required for the job are craned from the boat to the TP.

Other factors that will affect the nature and demand of the transfer onto the external ladder of the turbine include:

– The state of the ladder rungs *i.e.* build-up of deposits and wet rungs, both of which can compromise hand and foot placement and increase the risk of slippages
– If the WT is feeling seasick
– The clothing worn *i.e.* a sea survival suit restricting movement
– Previous climbs *i.e.* fatigue
– Light conditions

Transferring from the external ladder back onto the vessel requires communication between the deck hand and WT. Deck hands will count WT down from five and then require them to step back onto the vessel. The SMEs reported that there is a large element of trust as WT are stepping back blind, with guidance from the deck hand. Again, as with the transfer onto the external ladder, sea state will vary and thus the movement of the vessel will affect the size of the step back onto the vessel, the speed of the decent and distance the WT will have to climb down to the vessel. This again suggests a requirement for WT to be able to achieve hip flexion past 90°.

Ascent of the tower
When ascending the internal ladders Service Teams will be wearing PPE. Some companies' advocate that if a sea survival suit has been worn for transfer onto the turbine is should be removed at the TP, while other companies stipulate it should be worn for the entire ascent. The difference in thermoregulatory response, physiological and biomechanical demands has not been observed and will be quantified in section 4 of this report.

The approximate dimensions of internal ladders are:

– Total height TP to Nacelle – 80 m to 120 m in total height made up of several ladders requiring transfers, and thus allowing Service Teams to rest if needed.
– It was estimated that there could be between 5 to 10 transfers across ladders from the TP to the Nacelle.
– Ladder structure – 400 mm internal width; 470 mm external width, 300 mm from between rung mid-point to rung mid-point, if it is a rectangular rung this dimension is approximately 250 mm in depth and 320 mm in width. These dimension may vary depending on make and model of turbine.

Before beginning the ascent to the Nacelle, Service Teams will usually have rested for a minimum of 10 minutes, during this time they will be required to: prepare the kit for transport via the crane; undertake team talks; complete light manual dexterity tasks e.g. opening locks. When ascending only one Service Team member will climb a ladder at a time. The SME reported that whilst one of the Service Team is climbing the other is resting. There are no time constraints placed on a Service Team ascending the tower, and they can rest either at a transfer point or whilst climbing.

Using the turbine portrayed in Figure 2.4.1 and a team of three Service Technicians, the following was proposed by the SME: The Lead Technician will climb to Level A2 (approx. 10 m), whilst the other two technicians would climb straight to Tower Tower (approx. 30 m, Figure X). SME reported that this may take between 3 and 4 minutes, suggesting climbing rates between 25 rungs.min^{-1} and 33 rungs.min^{-1}. On reaching Tower Tower, Service Technicians tend to rest until the second and/or third Service Technicians has reached this level. It was suggested that the ascent to A4 could take longer, with all of the SMEs reporting a significant fatigue point approximately ¾ of the way up from Tower Tower. It was reported that between these two levels, the number of rests on the ladder may increase, as well as the time taken to complete the 30 m climb, suggesting climbing rates could drop to 20 rungs.min^{-1}. As the climb progresses up past A4 to the Yew and into the Nacelle, SME reported having to move through hatches of varying sizes and adopting positions requiring strength and mobility to manoeuvre through the hatches. At each level rests are taken. On reaching the Nacelle, Service Teams have a minimum of 10 minutes rest before beginning any other critical tasks. The time taken to complete the climb of the turbine suggests that the task requires predominantly aerobic and local muscular endurance capabilities.

It was suggested that in some instances WT found it easier and more efficient to climb with two points of contact. This is different to the Health and Safety Executive (HSE) guideline for the safe use of step ladders and ladders, which advocates three points of contact. It should be noted that this guideline appears to be for those free climbing, not those where they are attached to a fall arrest harness. Similarly the 'Good practice Guideline for Working at Height in the Offshore Wind Industry' (G9 Offshore Wind Health and Safety Association in association with the Energy Institute, 2014) states 'the probability of falling can be minimised by limiting the activities that are carried out from a ladder, and ensuring that users maintain three points of contact with the ladder'. Therefore, the techniques used by technicians need consideration. For the data collection phase of this project experienced technicians were asked to climb as they would and the number of points of contact was recorded.

During servicing it is likely that only the Lead technician will climb the complete tower more than once (*i.e.* two ascents and descents), due to them being responsible for the isolations within the turbine. Trouble-shooting teams may be required to climb the tower approximately 3 times.

SME reported that temperature and humidity within the Tower and Nacelle can vary dramatically throughout the course of the year and due to location. Temperature and humidity data are continuously collected in the Nacelle and could be used to help predict work rest schedules, when temperatures are extreme. Please refer to section 4 regarding working in the heat.

<u>*Descent of the tower*</u>

The SME reported that the descent of the internal ladder was less physically demanding than the ascent and took less time, with service technicians choosing to go from the top of the Nacelle to the TP without a rest (*NB.* The Lead Technician will break at A2 to remove the isolations). The SME also stated that they had timed the descent of the internal lift at 3,5 minutes and observed a number of Service Technicians descending at the same speed (*i.e.* A4 to the A2 approx. 60 m = a decent rate of approx. 57 rungs.min^{-1}). The SME experts also reported that in some cases Service Technicians would lean back against the wall and mainly descend with minimal stress going through their hands. This is not the case on a number of turbines and should not be considered common practice. In addition, those that did descend without the use of the wall stated that it was easier to maintain 3 points of contact during descent than ascent, where they tended to use two points of contact (see previous section).

<u>*Other physiological demanding tasks*</u>

The SME reported that the most physically demanding task Service Teams were required to complete was bolt torque and tensioning, which can comprise approximately 20 % of the service of one turbine. This task can require Service Technicians to manually handle the Tensions heads (Figure 2.4.3) of various weights (Table 2.4.3), used to tighten bolts, in a variety of awkward positions whilst standing, kneeling or seated, depending on the dimensions of the work space. The heaviest torque wrench used was measured at 7 kg. SME stated this was a whole body task, with fatigue accumulating in the shoulders, torso and lower back. This suggests Service Technicians will require elements of strength, muscular endurance and mobility to successfully undertake the task.

Figure 2.4.3: 19 kg (placed at the front of the picture) and 13 kg Tension Heads

Table 2.4.3: Tension heads and lifting requirements

Tension head mass (kg)	Lifting requirement
8,5	The 8,5 kg and 9 kg tension heads are often used in line with the shoulder (approx. 1,6 m). This can often require the tension head to be held in a single hand.
9	
13	Generally used horizontally from chest height (approx.1,5 m). This can sometimes require the tension head to be held in a single hand.
19	These are predominantly used at the Tower Tower section (Figure 2.4.1) of the turbine. The tension head is normally lifted to chest height, using an upright row movement.  

Other physically demanding tasks reported by the SME included:

- Using a torque wrench (heaviest 6,5 kg) at various heights from ground to 1 m.
- Manual handling kit (up to 27 kg) from the ground to 1 m.
- Fixing lights on a ladder (this was reported to be ergonomically difficult due to twisting and remaining in the harness all day, predominately felt in the lower leg calf muscles).
- Using brake callipers in the Yaw.
- Manipulating loads on cranes.

Balance of plant technicians (BPT)
BPT are responsible for non-wind turbine related work e.g. electrical lighting, fog sensors, fire alarms, temperature monitors, external lighting, and work on the substation. Similar to the Service Team, BPT have the same clothing requirement (*i.e.* PPE and survival suits) and emergency procedures. BPT do not work in the Nacelle and generally when working internally go from the TP down. In comparison with the Service Teams they ascend and descend shorter ladders (approx. 10 m) multiple times in a day, and are more likely to have multiple vessel transfers, with jobs lasting 45 minutes to 1 hour. Day to day, it was reported by the SME that BPT climb more, but in shorter bouts, with little to no rest unless waiting to be transferred to shore or transferring between turbines. Most of the critical tasks undertaken by the BPT have a high manual dexterity component. The most physically demanding task BPT perform is the manual handling of kit (various loads) using a 1:1 pulley system, as there is no crane in operation when working from the TP down.

Emergency response tasks
All WT will have completed a Global Wind Organisation (GWO) 'Working at Heights Course' (W@H), this will allow them to complete all casualty rescues that do not require a stretcher or spinal board. For incidences where a spinal board or stretcher are required, individuals must have the Advance Rescue certificate. If an emergency requires an advance rescue team, one must be available within 30 minutes (including a full descent, and vessel transfer to the TP). On arrival it is likely that these team will ascend straight to the casualty without rest. This suggests that advanced rescue teams may be required to be fitter than the WT. Following the casualty evacuation, teams in that turbine will cease work for the day.

SMEs identified four tasks they perceived to be the most physically demanding:

- Hauling a casualty up the turbine.
- Lowering the casualty down the turbine.
- Extracting a casualty from the Hub.
- Extracting a casualty from under gear boxes and generators.

The Methods of Best Practice (MOBP) used to perform these tasks are taught during the Working at Height (W@H) and Advanced Rescue courses. The SME stated that in any rescue the first choice is always to lower a casualty rather than haul the casualty up the turbine due to the greater physical demand required to haul a casualty.

The hauling method for WT, if an automated system (e.g. UPs Rescue) is not available, is a standard 6 to 1 (it is recommended that these ratios are checked for accuracy) pulley, although this is not rated for lifting so will always be backed up by work positioners that only has a reach 4 m. Therefore, this may be considered the minimum distance WT would be expected to haul a casualty, although in some cases this may have to be repeated multiple times.

The mass of the WT population is unknown, some weight restrictions are applied due to the maximum loads the climbing kit can withstand *i.e.* the maximum mass of a casualty, including PPE, could be 136 kg (not including the spinal board (approx. 6 kg to 8 kg) and/or basket stretcher (approx. 10 kg to 13,5 kg)). This load is based on the 'Cab Lock' system used by the SME used in this critical task analysis.

2.4.2 Review of current physical employment standards for offshore wind technicians

Each of the five organisations who responded to the email stated that they used either the *Oil or Gas Industries Offshore Medical Aspects for work Offshore: Guidance for Examining Physicians* (Oil and Gas UK, 2006) or the *Medical Fitness to Work – Wind Turbines* (RenewableUK, 2013) (Table 2.4.1), with all five using medical standards as opposed to fitness standards.

Table 2.4.1: Overview of the current medical from the five respondents

Organisation	Standard and test used to assess fitness	Level/Pass criteria
1	*Oil and Gas Offshore Medical – Chester Step test*	35 $mL.kg^{-1}.min^{-1}$
2	*Chester Step test*	Not reported
3	*Renewables UK: Medical Fitness to Work – Wind Turbines – Chester Step test*	35 $mL.kg^{-1}.min^{-1}$
4	*Oil and Gas Offshore Medical – Chester Step test*	Level 'Good'
5	*Oil and Gas Offshore Medical – no aerobic test*	N/A

Setting an aerobic standard

Two standards are presently used by the five organisations. These include and aerobic standard of 35 $mL.kg^{-1}.min^{-1}$ and a pass of 'good'. The aerobic score of 35 $mL.kg^{-1}.min^{-1}$ taken from the *Oil and Gas Industries Offshore Medical Aspects for work Offshore: Guidance for Examining Physicians* (Oil and Gas UK, 2006) is based on the Emergency Response Team (ERT) aerobic standard, stating that: '*based on the experience of other occupational groups, it has been determined that a* $\dot{V}O_{2max}$ *of 35* $mL.kg^{-1}.min^{-1}$ *is the minimum that would indicate that individuals will have the physical capability adequate for normal ERT duties*' (Oil and Gas UK, 2006 pg. 3–5 para 2.3).

Whilst ERT may be required to undertake a critical task such as ladder climbing, the performance of this task could be very different from that of WT in terms of duration, speed, clothing ensemble and load carried. Thus, the problem with using 35 $mL.kg^{-1}.min^{-1}$ as a pass score is that is does not directly reflect the critical task of WT and as such may not be legally defensible if challenged in a Court of Law.

The *Medical Fitness to Work – Wind Turbines* (RenewableUK, 2013) goes some way to address the non-specific nature of using the Oil and Gas standard stating: '*that neither the MCA or the Oil and Gas UK medical certification schemes were designed to reflect the specific risks that are particular to the renewable energy sector as reflected in these guidelines*' (RenewableUK, 2013 pg 8).

Whilst this document acknowledges that there are a range of fitness components required to successfully undertake the job of a WT, and provides a brief overview of the tasks undertaken by WT, it states that: '*to date there has been no industry specific guidance or information that clearly sets out the scope or requirements for medical fitness assessments particular to the renewable energy sector*' (RenewableUK, 2013 p 3).

Thus, the approach adopted in this document relies on the subjective decisions of the occupational physician performing the assessments, with the only pass/fail recommendation being given for the assessment of aerobic capacity based on normative data: '*that estimated* $\dot{V}O_{2max}$ *in those working on wind turbines should be at least 35 mL/kg/min*' (RenewableUK, 2013 pg 12).

Basing an aerobic score on normative data may highlight individuals with conditions that compromise safety by creating a risk of falling or sudden incapacity, but it does not necessarily ensure capability for regular climbing of vertical ladders and for working in hot and/or confined spaces, as these have not been quantified and could exceed what is the population norm.

The second method, a score of 'good', means that employees' aerobic capacity could range from 33 $mL.kg^{-1}.min^{-1}$ to 59 $mL.kg^{-1}.min^{-1}$, whilst this is acceptable for health-based screening, it does not necessarily ensure that employees have the required aerobic fitness to successfully undertake the critical tasks of a WT. In addition, having a range of possible scores based on age and sex means that selection is both age and sex biased. For example a 'good' score for a male aged 20 to 29 results in a minimum estimated aerobic capacity of 44 $mL.kg^{-1}.min^{-1}$ (range 44 $mL.kg^{-1}.min^{-1}$ to 55 $mL.kg^{-1}.min^{-1}$), whilst a female aged 40 to 49, who may be expected to undertake the same critical task as the male, would have a minimum estimated aerobic capacity of 34 $mL.kg^{-1}.min^{-1}$ (range 34 $mL.kg^{-1}.min^{-1}$ to 42 $mL.kg^{-1}.min^{-1}$). The implementation of a tasked-based PES into an occupation where there is a known physical demand ensures that employment selection is fair and unbiased. These standards generally base the suitability for employment on the physical and physiological components associated with the safe and successful completion of tasks that are considered to be generic and critical, and therefore essential, for a specific job, thereby guaranteeing employment is free from age and sex discrimination.

<u>*The use of the Chester Step Test*</u>

The Chester step test was originally designed to predict $\dot{V}O_{2max}$ for fire brigades in Britain, Europe, USA and Asia (Sykes and Roberts, 2004), and is currently widely used by airport fire-fighters, ambulance services, health authorities, corporate institutions and the Oil and Gas Industry. Unlike many other step tests, the Chester step test uses an incremental exercise procedure, whereby an initial step rate of 15 $steps.min^{-1}$ is set for the first 2 minutes. This is then increased by 5 $steps.min^{-1}$ in 2 minute stages thereafter, until participants reach 80 % of age-estimated HR maximum (Karvonen *et al.* 1957 [220 – age]) and/or a rate of perceived exertion (RPE) of 14 on Borg's 6 to 20 scale (Borg, 1982). The Chester step test prediction equation is based on 68 participants (n = 47 males; n = 21 females), aged 18 years to 52 (the frequencies of the distribution are unknown), across a range of fitness levels (25 $mL.kg^{-1}.min^{-1}$ to 68 $mL.kg^{-1}.min^{-1}$, distribution unknown). Aerobic capacity was predicted by plotting a visual line between the exercise stage, and HR, projecting the line up to a predicted maximum HR and estimating the corresponding $\dot{V}O_{2max.}$ A high overall correlation was found (0,92) between $\dot{V}O_{2max}$ and the results of the Chester step test with a regression equation $\dot{V}O_{2max}$ = 0,964 x 1,007(Chester step test score) (Sykes and Roberts, 2004). The higher correlation reported for females (0,95) than males (0,87) could be a consequence of a smaller number of female participants, with less diversity in factors such as age, height and mass.

Sykes and Roberts (2004) concluded that the Chester step test was shown to be a valid tool for the estimation of $\dot{V}O_{2max}$ within this group. Furthermore, it was reported that due to the small error of measurement (3,9 $mL.kg^{-1}.min^{-1}$) that this method was sufficiently sensitive to detect changes in increases in aerobic capacity greater than 3,8 $mL.kg^{-1}.min^{-1}$ and losses in aerobic capacity or greater than 5,2 $mL.kg^{-1}.min^{-1}$ from the base line measurements. Subsequently, Buckley *et al.* (2004) re-examined the reliability and validity of the Chester step test with 13 participants (n = 7 male; n = 6 female). One of the main assumptions underpinning the Chester step test is that the relationship between $\dot{V}O_{2max}$ and HR is linear in relation to increments in exercise. However, a significant difference that was demonstrated between actual and predicted maximum HRs (Buckley *et al.* 2004). Thus, it was concluded that the validity of the prediction was questionable with error rates ranging between 11 % (overestimation) and 19 % (underestimation), which is considered suitably sensitivity for health promotion, but not for employment decisions. The Chester step test was found to be reliable on a test re-test basis (Buckley *et al.* 2004). Therefore, if the Chester Test is being used to determine aerobic capacity, the user should consider introducing 'Pass', 'Borderline', and 'Fail' categories to take into account the inherent error within the prediction equation (Tipton *et al.* 2013)

Since its introduction the Chester step test has been modified to allow step height to be determined by an individual's age and training history. However, these changes have not been validated or reliability assessed (Buckley *et al.* 2004). The Chester step test has a number of potential sources of error. The first is that a visual line of best fit is used rather than a calculated line of best-fit. Second, there is an error associated with using a predicted HR maximum (PHRM) rather than actual HR maximum (HRM).Thirdly, there is an assumption that the relationship between HR and $\dot{V}O_2$ remains linear as exercise intensity increases, whereas this relationship has been found to be curvilinear at exercise intensities near exhaustion, or altered by ambient temperature (Buckley *et al.* 2004).

One study has shown that the accuracy of PHRM ranged from 47 % to 69 % for the men and women (Whaley, 1992). Data from the study revealed that older individuals commonly exceed the PHRM (Whaley, 1992). Whaley (1992) also found that including information about age, smoking habits, body weight, and resting HR, helped to identify those who differed significantly from the PHRM. In addition, the test requires individuals to work at 80 % of their PHRM; this may place some individuals under considerable physiological strain, particularly if they have low fitness levels.

<u>Other physical requirements</u>
It is clear from the critical task analysis that WT require more physical attributes than aerobic fitness alone, these included strength, strength endurance and mobility of the upper and lower body. Therefore, it is advised that these be quantified and included into the current screening protocols. The study reported below in section 3 was designed to help to determine these physical attributes.

2.5 SUMMARY

The previous sections have identified five critical tasks perceived to be the most physically demanding for WT:

1. Transfer from the vessel to the TP – the type of turbine, sea state and condition of the ladder will largely influence the transfer.
2. Ascent of the internal ladder – climbing 80 m to 120 m without a time constraint and with the ability to take multiple rests.
3. Manoeuvre through hatches – the weight of the hatch door, size and orientation will affect the strength and mobility required for this task.
4. Torque and tensioning – lifting up to 19 kg multiple times.
5. Haul a casualty up the tower – one haul can be up to 4 m before the kit has to be readjusted, the MOBP are taught during the W@H and AW@H courses, the mass of casualty is yet to be determined.

One thing that became clear from the critical task analysis was that due to variations in turbines, standardising certain tasks such as the transfer from the vessel is extremely difficult. Further analysis beyond the scope of this project would be required to assess:

1. The impact of various ladder conditions brought about by the environment (e.g. wet slippery rungs) on the biomechanical demands and injury risk of transferring onto the ladder from the vessel and climbing the first few rungs.
2. The impact of sea state on the physical requirements to transfer onto the ladder.

The critical tasks identified require a range of physical attributes including: mobility, upper and lower limb strength and strength-endurance, and aerobic capacity. Further investigation would be required to quantify the physical demands of the critical tasks. In order to do this the industry would need to agree minimum acceptable operating procedures and MOBP for tasks where the load and repetitions could not be quantified objectively. In addition, the current medical fitness standards available for the WT are limited, and often not based on the actual job demands associated with working offshore on wind turbines. Thus, considerations should be given to:

1. Developing an industry standard for the minimal acceptable rate to ascend an internal ladder.
2. Establishing the MOBP for climbing a ladder, the HSE recommend 3 points of contact whilst experience technicians tend to opt for two points of contact. The implication of using either technique from a biomechanical, physiological and safety aspect should be considered.
3. The quantification of aerobic standards based on the minimal acceptable rate, using the MOBP, to ascend an internal ladder.
4. Reviewing the current demographic of the WT, thus enabling emergency response tasks to be quantified in terms of a minimal load (mass) WT are expected to haul up a tower.
5. The physical requirement to open and manoeuvre through hatches.
6. The production of a task-based defensible PES.

3 ERGONOMIC ASSESSMENT

3.1 OBJECTIVES

To undertake a detailed ergonomic assessment of ladder climbing, identifying the key risks associated with this task, and to determine if the current assessments of fitness are appropriate for predicting ladder climbing ability.

3.2 INTRODUCTION

The methodology employed for the ergonomic assessment of ladder climbing was based on the gaps existing in the literature (section 1) and the results of the Critical Task Analysis (section 2). This study looked to provide the first assessment of ladder climbing (120 m) over repeated bouts (3 x 120 m climbs). Both physiological and biomechanical analysis techniques were used to assess performance.

3.3 METHODS

3.3.1 Participants

Seventeen participants (3 = female; 14 = male) were tested. Of these 10 were novice climbers (1 = female; 9 = male) and seven were current WT (2 = female; 5 = male).

3.3.2 Procedures

On arrival to the University of Portsmouth Laboratories WT, only, were asked to swallow a temperature pill 90 minutes before commencing exercise (see 3.3.3). All participants were then familiarised (first shown then given time to practice) with the ladder ergometer (HP Cosmos, Figure 3.3.2.1) and manual dexterity task.

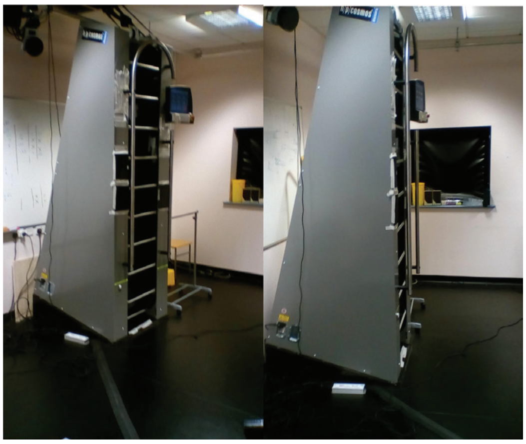


Figure 3.3.2.1: Ladder ergometer. HP Cosmos ladder with wedge underneath to create a vertical ladder treadmill

All participants' height, mass, body composition, and leg length were recorded prior to undertaking the Chester Step test (see 3.3.3). Following this, participants were asked to don a work overall, steel toe-capped boots, full climbing harness and accessories (*NB*: non-technicians had additional weight added to them to ensure they were climbing with the same load as the WT), helmet and gloves (*NB.* As stated above, for the first trial WT only were asked to don full PPE and their sea survival suit). A series of electrodes were placed on the forearm and calf to measure muscle activity via EMG, and kinematic markers placed on the body (detailed procedures provided at 3.3.3).

Participants were required to rest seated for 5 minutes to allow for a resting blood lactate (BLa) to be taken. Maximum grip strength and 30 s grip endurance were measured, participants were then asked to undertake a short manual dexterity task (MDT) (detailed procedures provided at 3.3.3).

Participants were asked to climb to the top of the ladder ergometer whilst it was stationary and descend five rungs, this was repeated three times to allow for EMG and kinematic data to be recorded. Following this, participants climbed 30 m on the moving ladder ergometer at a self-selected pace using their preferred climbing technique (neither the speed or technique were standardised as these could not be established during the critical task analysis, thus this study was used to investigate speed and technique difference across groups). On completion, participants were seated, RPE and grip strength were recorded and a rest period equal to the time it had taken to climb the previous 30 m was provided. Participants repeated this four times to complete a total of 120 m. On completion, grip strength and RPE were recorded prior to participants climbing to the top of the static ladder ergometer and descending five rungs, this was repeated three times to allow for EMG and kinematic data to be recorded. During the simulated ladder climb $\dot{V}O_2$ and HR were measured continuously (detailed procedures provided at 3.3.3). EMG and kinematic data were collected continuously (detailed procedures provided 3.3.3). Participants were then seated, grip strength and 30 s endurance were measured and BLa recorded 3 minutes post exercise. The MDT was then repeated.

Based on findings from the critical task analysis, this sequence was completed three times, each 120 m climb was separated by a minimum of 1 hour 15 minutes of rest.

3.3.3 Measurements

<u>*Deep body temperature*</u>
An ingestible telemetry pill (Jonah Ingestibles, US), which transmits a radio frequency correlated with its temperature, was swallowed with a small amount of tepid water by the WT at least 90 minutes before exercise. Gastrointestinal deep body temperature (Tgi) from the pill was recorded using a receiver unit (Mini Mitter, US) and measured pre and post climbs and every 2 minutes post climb until a plateau or reduction in temperature was observed. The data collected are presented and discussed in section 4.

<u>*Mass*</u>
The participants were weighed to the nearest 0,05 kg (Model B150S Sartorious, UK) in minimal standard clothing (shorts and T-shirt, and socks without shoes).

<u>*Height*</u>
With standard clothing, shoes removed the participant stood on the stadiometer (Seca Ltd, Leicester, UK) with their feet together. Buttocks, feet and scapulae were in contact with the back of the stadiometer and the participant looked directly ahead. The slide rule was lowered until it came into contact with the top of the head and stature was read to the nearest 0,1 cm.

Anthropometry

Subcutaneous fat skinfold measurements were taken at eight sites (biceps, triceps, subscapular, iliac crest, supraspinale, abdominal, front thigh, medial calf) using skinfold calipers (Harpenden, UK) in accordance with the technique and calculations described by Durnin and Womersley (1974).

Leg length

Femur and tibia length (cm) were measured on the right side using a measuring tape. Femur length was measured from the ASIS in the hip to the midpoint of the patella and tibia length was measured from the midpoint of the patella down to the calcaneus in the ankle.

Chester Step Test

Participants were required to step up onto a 30 cm step (if under 40 years old) and 25 cm (if over 40 years old). Once on the step with both feet the participant then stepped back off the step before repeating the movements in time with a metronome. The Chester Step test is multi-staged, and started at 15 steps.min^{-1}. Each stage lasted 2 minutes, on completion RPE and HR were recorded before step rate was increased by 5 steps.min^{-1}. Participants continued stepping until they reached 80 % of their age predicted maximum HR and/or 14 on the RPE scale, or complete level 5.

Electromyography (EMG)

The EMG equipment included the data logger (Biometrics Data Log P3X8, Biometrics Ltd, UK) and passive surface electrodes (Biometrics Pre- Amplifiers, Biometrics Ltd, UK). To measure muscle activity, surface EMG (mV) was employed, during which the participants had surface electrodes placed on the selected muscles; gastrocnemius (G), flexor digitorum superficialis (FD), biceps brachii (BB) and anterior deltoid (AD). These muscles were chosen because they include the primary muscles used in climbing (see section 1). SENIAM guidelines were followed (http://www.seniam.org/) for specific electrode placement on each muscle. To obtain the best possible skin-electrode contact and, in turn, improve the accuracy of the EMG signal, it was important to prepare the skin; this involved cleaning the skin with an alcoholic wipe, and dry shaving the area. A reference electrode was placed on the clavicle of each participant.

Kinematic data

A Qualisys Optoelectronic system (OQUS 300, Sweden) captured each participant climbing using 10 cameras, sampling at 250 Hz. Cameras were set at differing heights in a circle around the calibrated volume, in order to maximise marker visibility and data capture. The ladder climb was conducted in an area measuring 4 m x 4,5 m x 3 m, this formed the calibrated area filmed for the study. This area was calibrated using the L-frame and Wand methods (Qualisys, Sweden) prior to arrival of the participant.

A total of 48 passive retro reflective markers (12 mm) were placed on anatomical landmarks identified using the Visual 3D software marker system (C-Motion, USA). These markers were specifically chosen to allow coordination between upper and lower body to be calculated, particularly with regard to limb contact with the ladder rungs.

A static trial of each participant was captured before beginning the movement. This allowed the adjusted body segments to be calculated. During the data collection, cluster markers were used as tracking markers at the midpoints of each segment. This allowed the movements of segments to be calculated in the Visual 3D analysis software, and subsequently enabled direct comparison with the movement of segments across conditions.

Blood Lactate (BLa)

BLa was recorded from the earlobe sample using a blood analyser (Lactate Plus, Lactate Meter, Nova Biomedical, USA) a total of six times during the experimental session. A small blood sample (0,7 μL) was taken by a pin prick to the ear lobe and analysed via a test strip. The test sample was disposed of, in a biohazards waste bag, 60 s after the sample has been taken.

Grip Strength and Endurance
Grip strength and grip endurance sustained over 30 s were measured using a Precision Dynamometer G100 (Biometrics Ltd, Gwent, UK) which is accurate to 0,1 kg and was used to measure maximum grip strength (Figure 3.3.2). Maximum grip strength tests were undertaken three times for each hand, allowing 30 s rest between tests of the same hand (Douris *et al.* 2003). The endurance tests were completed once per hand, although they were repeated if the dynamometer slipped or was not maintained in the correct position for the duration of the test. Grip endurance was recorded as an average over the final 18 s. The dynamometer was zeroed before each test; the elbow was at 90 degrees. The hand did not tilt, rest on the leg or table, and grip was a maximal squeeze not a snatch.

Figure 3.3.2: Precision Dynamometer G100

Heart Rate (HR)
HR was recorded using the Polar Team System, which was attached prior to the session. The HR monitors were analysed at 20 s intervals.

Oxygen Consumption
The metabolic response was measured using a Metamax 3B (Cortex, Italy), for the duration of the exercise. Breath by breath data were recorded and converted to 20 s collections. This required participants to wear the system attached to the back of the body and a face mask for the duration of the climbs.

Rate of Perceived Exertion (RPE)
RPE provides a subjective method of quantifying exertion placed on the participant. At the end of each climb, the participants were asked to provide an RPE using the 6–20 RPE scale proposed by Borg (1982).

Manual Dexterity Test
The manual dexterity test resembled the commercially available hand tool dexterity test (Lafayette Instrument Evaluation, UK). This test measures proficiency in using ordinary mechanical tools. The test consists of tools and two uprights with bolts (Figure 3.3.3). The object was to disassemble all the bolts from one upright and reassemble them on corresponding rows of the other upright with the heads of the bolts inside. Each bolt was tighten using a pre-set torque wrench.

Figure 3.3.3: Example manual dexterity test

3.3.4 Data analysis

EMG Data
The EMG data were post processed using DataLink management and analysis software (Biometrics Ltd. UK). A differential technique was performed to reduce cross-talk of the EMG signal. The Raw EMG signal was processed in the time domain by computing the root mean square (RMS) value of the rectified signal, and then filtered as appropriate.

The peak RMS data were calculated during the entire trial for each participant. All values exhibited by each participant in the trials were expressed as a percentage of each participant's peak value exhibited during the trial. This was achieved using the peak dynamic method. Any differences in activity in the muscles between the trials were reported as a percentage difference for each participant.

Kinematic Data
Markers on the body were identified and reconstructed in Qualisys Track Manager Software (Qualisys, Sweden), with tracking parameters of 0,25 mm marker detection error and a maximum interpolation of 10 frames. The global coordinate system (GCS) in the laboratory identified x as the line of progression (anteroposterior axis), y as the mediolateral axis, and z as the vertical axis. All markers were filtered using an optimised Butterworth filter within the Visual3D software prior to further analysis. The markers recorded in the static trial were exported as a C3D file to Visual3D where the segments of the body were reconstructed. Once the model had been reconstructed, it was applied to the movement trials, and the segments identified were presented allowing for calculation of displacements and velocities of the individual segments. Additional calculations on phase angles with be presented in the final report. Markers were also placed on the ladder to allow distances between the limbs of the participant and the ladder to be calculated at all times throughout the trial. Kinematic data was assessed between each of the three climbs and also between the beginning and end of the trial.

Statistical Analysis
Data were statistically analysed using IBM SPSS 24,0 for Windows (SPSS Inc, Chicago, IL). Tests of normality were conducted to assess if the data were parametric using Skewness and Kurtosis. If the data were found to be parametric, repeated measures and mixed model ANOVAs were used to determine significant differences and interactions. *Post-hoc* analysis consisted of paired and independent samples *t*-tests with Bonferroni corrections applied.

Effect sizes were calculated using Cohen's *d* (Cohen, 1988). If data were non-parametric, a mixed model ANOVA was run to determine any significant differences and interactions, as there is no non-parametric equivalent. *Post-hoc* analysis consisted of Wilcoxon Signed-rank, Friedmans, Mann-Whitney U and Kruskal Wallis tests with Bonferroni corrections applied. Effect sizes were calculated using the following equation $Z/\sqrt{n}$.

3.4 RESULTS

<u>*Anthropometric and Fitness*</u>
Table 3.4.1 details the demographic, anthropometric and fitness (aerobic and strength) data of the WT, novice climbers and combined. There were no significant differences (p > 0,05) between the WT and the novice climbers suggesting a suitable comparison between the two groups was possible.

Table 3.4.1: Demographic, anthropometric and fitness data (n = 17; WT n = 7; Male = 5, Female = 2: Novice Climbers n = 10; Male = 9, Female = 1)

		WT	Novice Climbers	Combined
Age (yrs)	Mean	36	29	32
	SD	6,82	10,61	9,60
	Min	29	19	19
	Max	50	50	50
Height (cm)	Mean	179,83	181,76	180,96
	SD	6,78	8,64	7,76
	Min	167,5	161,1	161,1
	Max	185,6	192,9	192,9
Mass (kg)	Mean	77,64	83,15	80,88
	SD	15,17	11,93	13,20
	Min	59,00	62,5	59,00
	Max	100,00	102,5	102,5
Sum of skinfolds (mm)	Mean	110,86	117,24*	114,45**
	SD	38,07	39,33	37,62
	Min	64,4	53,4	53,4
	Max	168,1	176,75	176,75
Upper Leg Length (cm)	Mean	50,57	51,89	51,35
	SD	6,67	3,12	4,75
	Min	37,50	47,50	37,50
	Max	56,50	58,50	58,50

Table 3.4.1: Demographic, anthropometric and fitness data (n = 17; WT n = 7; Male = 5, Female = 2: Novice Climbers n = 10; Male = 9, Female = 1) (continued)

		WT		Novice Climbers		Combined	
Lower Leg Length (cm)	Mean	44,20		48,19		46,91	
	SD	5,20		5,20		5,49	
	Min	39,00		42,30		39,00	
	Max	49,40		56,00		56,00	
Aerobic capacity $\dot{V}O_{2max}$ (mL.kg^{-1}.min^{-1})	Mean	52,86		52,40		52,59	
	SD	7,62		7,62		6,80	
	Min	48,00		36,00		36,00	
	Max	61,00		65,00		65,00	
Max Grip Strength (kg)		Left	Right	Left	Right	Left	Right
	Mean	39,09	40,54	43,74	44,45	41,82	42,84
	SD	6,69	8,73	7,40	7,73	7,29	8,13
	Min	29,30	28,30	35,80	35,50	29,30	28,30
	Max	46,60	53,50	59,60	61,70	59,60	61,70
Grip Endurance (kg)* **		Left	Right	Left	Right	Left	Right
	Mean	26,07	25,24	25,89	23,55	25,96	24,25
	SD	5,02	4,20	5,30	5,37	5,03	4,85
	Min	17,00	18,50	19,10	17,70	19,10	17,70
	Max	30,90	30,60	32,00	31,20	32,00	31,20

* n = 9
** n = 14
*** Grip endurance is represented by the average grip sustained over the final 18 s of the 30 s test.

<u>*Climbing Times and Speed*</u>

Time Spent Climbing/Active
The time spent climbing 120 m, irrespective of climbing experience, was not significantly different across the three climbs, with a maximum variation of 30 s between Climb 1 and 3. There were no significant differences between WT and novices, however high effect sizes were observed (suggesting a meaningful difference). Based on the mean data and high effect sizes, WT spent, 2 min 33 s (Climb 1; *d* = 1,26; *NB:* WT had the addition of a sea survival suit), 3 min 22 s (Climb 2; *d* = 1,12), and 2 min 20 s (Climb 3; *d* = 1,35) less time climbing than the novice climbers (Tables 3.4.2 to 3.4.4). It is likely that a Type 2 error (stating there is not difference when there is a difference) has occurred, due to:

– Unequal sample sizes (*i.e.* WT = 7; Novices = 10)
– Differences in SD between the two groups. WT demonstrated a small SD (small variation around the mean), whilst the novice climbers a large SD (large variation around the mean).
– Low participant numbers for WT

Therefore, when comparing WT to novices differences will be inferred based on effect sizes.

Climbing Speed

Self-selected climbing speed ranged between 9 $m.min^{-1}$ (30 $rungs.min^{-1}$) and 19,5 $m.min^{-1}$ (65 $rungs.min^{-1}$) for the novice climbers and 13,5 $m.min^{-1}$ (45 $rungs.min^{-1}$) to 20 $m.min^{-1}$ (66,67 $rungs.min^{-1}$) for WT. Twelve (WT = 5; Novice = 7) chose to increase speed over the 12 x 30 m climbs. Two novice climbers and one WT decided to reduce the speed and two (WT = 1; Novice = 1) kept at the same speed for all the climbs.

End climbing speed *i.e.* the speed chosen by the participant to climb (this speed does not take into account the time take to get up to speed following each stop), irrespective of climbing experience, was significantly different ($F_{(1,514,22,703)} = 7,816$; $p = 0,002$) across the three climbs. With Climb 1 (14,4 [2,9] $m.min^{-1}$ [48 $rungs.min^{-1}$]) reporting a significantly ($t_{(16)} = -2,890$; $p = 0,011$; $d = -0,38$) slower climbing speed than both Climb 2 (15,5 [2,9] $m.min^{-1}$ [51,67 $rungs.min^{-1}$]) and Climb 3 (16,2 [3,3] $m.min^{-1}$ [54 $rungs.min^{-1}$]; $t_{(16)} = -3,249$; $p = 0,005$; $d = -0,58$), there was no significant difference between Climbs 2 and 3.

Cumulative Rest Time (taken during the 30 m climbs) and Number of Rests Taken During Each Climb

Cumulative rest time irrespective of climbing experience was significantly different ($F_{(2,30)} = 7,288$; $p = 0,003$). With Climb 1 containing significantly less rest time than both Climb 2 ($t_{(16)} = -2,511$; $p = 0,023$; $d = -0,16$) and Climb 3 ($t_{(16)} = -3,269$; $p = 0,005$; $d = -0,28$). However, the effect sizes suggest that these differences, whilst significant, are not meaningful, likely due to the high SD observed (Tables 3.4.2 to 3.4.4). A significant interaction ($F_{(2,30)} = 7,288$; $p = 0,003$) was reported between cumulative rest time and climbing ability (*i.e.* WT vs novice). It is suggested that WT did not significantly increase rest time across the three climbs, with a small average increase of 17 s from Climb 1 to 3, whilst the novice climbers increased rest time by, on average, 2 min 28 s (Tables 3.4.2 to 3.4.4).

This increase in rest time was reflected in the number of rest breaks taken during the four 30 m climbs that made up each of the three 120 m climbs. Two WT did not take any rest during the 12 x 30 m climbs (3 x 120 m). WT remained consistent taking, a median (range), 4 (0 to 5) rests, whilst the novice climbers increased from 4 (1 to 11) on Climb 1 to 7 (1–13) by Climb 3 (Tables 3.4.2 to 3.4.4).

Total Time (120 m climb time + cumulative rest time)

Total climbing time irrespective of climbing experience was significantly different ($F_{(2,30)} = 4,453$; $p = 0,020$). With Climb 1 being significantly faster than both Climb 2 ($t_{(16)} = -2,643$; $p = 0,018$; $d = -0,099$) and Climb 3 ($t_{(16)} = -2,723$; $p = 0,015$; $d = -0,14$). However, the effect sizes suggest that these differences, whilst significant, are not meaningful – likely due to the high SD observed (Tables 3.4.2 to 3.4.4). There was no significant difference between Climbs 2 and 3.

Based on the mean data, WT climbed each 120 m, 3 min 13 s (Climb 1; $d = 1,04$; *NB:* WT had the addition of a sea survival suit), 4 min 25 s (Climb 2; $d = 1,02$), and 5 min 14 s (Climb 3; $d = 1,05$) faster than the novice climbers. With the WT climbing time remaining relatively consistent, whilst the novices became slower on each climb (Tables 3.4.2 to 3.4.4).

Table 3.4.2: CLIMB 1: Climbing and rest times for ascending 120 m (4 x 30 m climbs) (n = 17; WT n = 7; Male = 5, Female = 2: Novice Climbers n = 10; Male = 9, Female = 1)

		WT*	Novice Climbers	Combined
Time spent climbing 120 m (4 x 30 m climbs) (min:s)	Mean	8:07	10:40	9:57
	SD	0:33	3:08	2:21
	Min	7:15	7:30	7:15
	Max	9:45	16:16	16:16
Time spent resting during 4 x 30 m climbs (min:s)**	Mean	3:12	4:52	4:11
	SD	2:43	3:33	3:15
	Min	0	0:30	0
	Max	6:41	10:35	10:35
No. of rest breaks taken during 4 x 30 m climbs	Median	4	4	4
	Range	5	11	12
	Min	0	1	0
	Max	5	12	12
Total climbing time (min:s)* **	Mean	11:19	15:32	13:48
	SD	2:50	5:20	4:51
	Min	7:35	8:00	7:35
	Max	14:33	24:43	24:43

* This climb was undertaken with the addition of a sea survival suit
** The number and the duration of the rest taken during the 30 m climb was self-selected
*** The rest time reported only includes rest taken during the climbs it does not take into account the rest provided after each 30 m climb which was set for each individual based on the time taken to climb the proceeding 30 m.

Table 3.4.3: CLIMB 2: Climbing and rest times for ascending 120 m (4 x 30 m climbs) (n = 17WT n = 7; Male = 5, Female = 2: Novice Climbers n = 10; Male = 9, Female = 1)

		WT	Novice Climbers	Combined
Time spent climbing 120 m (4 x 30 m climbs) (min:s)	Mean	8:10	10:32	9:34
	SD	0:26	2:44	2:23
	Min	7:32	7:07	7:07
	Max	9:34	16:49	16:49
Time spent resting during 4 x 30 m climbs* (min:s)	Mean	3:31	5:35	4:44
	SD	3:12	3:51	3:38
	Min	0	0:30	0
	Max	7:23	11:32	11:32
No. of rest breaks taken during 4 x 30 m climbs	Median	4	5	4
	Range	5	12	13
	Min	0	1	0
	Max	5	13	13

Table 3.4.3: CLIMB 2: Climbing and rest times for ascending 120 m (4 x 30 m climbs) (n = 17WT n = 7; Male = 5, Female = 2: Novice Climbers n = 10; Male = 9, Female = 1) (contiuned)

		WT	Novice Climbers	Combined
Total climbing time (min:s)**	Mean	11:42	16:07	14:18
	SD	3:24	5:50	5:20
	Min	7:32	10:36	7:32
	Max	15:45	25:02	25:02

* The number and the duration of the rest taken during the 30 m climb was self-selected
** The rest time reported only includes rest taken during the climbs it does not take into account the rest provided after each 30 m climb which was set for each individual based on the time taken to climb the proceeding 30 m.

Table 3.4.4: CLIMB 3: Climbing and rest times for ascending 120 m (4 x 30 m climbs) (n = 17; WT n = 7; Male = 5, Female = 2: Novice Climbers n = 10; Male = 9, Female = 1)

		WT	Novice Climbers	Combined
Time spent climbing 120 m (4 x 30 m climbs) (min:s)	Mean	7:58	10:18	9:20
	SD	0:23	2:37	2:18
	Min	7:21	7:02	7:02
	Max	8:22	14:23	14:23
Time spent resting during 4 x 30 m climbs* (min:s)	Mean	3:29	6:24	5:12
	SD	2:53	4:20	2:18
	Min	0	0:30	0
	Max	7:50	13:22	13:22
No. of rest breaks taken during 4 x 30 m climbs	Median	4	7	5
	Range	5	13	14
	Min	0	1	0
	Max	5	14	14
Total climbing time (min:s)**	Mean	11:27	16:41	14:32
	SD	2:58	6:08	5:37
	Min	7:32	7:50	7:32
	Max	15:56	26:00	26:00

* The number and the duration of the rest taken during the 30 m climb was self-selected
** The rest time reported only includes rest taken during the climbs it does not take into account the rest provided after each 30 m climb which was set for each individual based on the time taken to climb the proceeding 30 m.

<u>*Metabolic and Cardiorespiratory*</u>

Aerobic and Anaerobic Contribution to Work

To provide an insight into the physical demand of ascending a 120 m vertical ladder, the respiratory exchange ratio (RER) was used to estimate the proportion of time spent metabolising energy aerobically (RER </= 1) and anaerobically (RER > 1). Calculations were based on the cumulative time of each of the four 30 m climbs and the three rest breaks provided after the first three climbs. The data are presented as a percentage of this total time. Table 3.4.5 details the time spent exercising (*i.e.* climbing) and the time spent resting (*i.e.* a cumulative total of prescribed rest breaks and self-selected rest breaks taken during each of the 30 m climbs). Table 3.6.5 demonstrates that in order to complete a 120 m, climbers were exercising/working approximately a third of the total time.

Table 3.4.5: Mean (SD) time spent exercising (*i.e.* climbing) and time spent resting (*i.e*. a cumulative total of prescribed rest breaks and self-selected rest). (Climb 1, n = 15 [WT = 6; Novice = 9]; Climb 2, n = 15 [WT = 6; Novice = 9]: Climb 3 n = 14 [WT = 5; Novice = 9])

Climb	Total time (min:s)	Climbing (min:s)	Resting (min:s)	Climbing (%)	Resting (%)
1					
Mean	28:31	9:44	18:47	35	65
SD	8:19	2:23	6:18	6	6
2					
Mean	28:22	9:19	19:03	34	66
SD	8:39	2:10	7:28	8	8
3					
Mean	30:30	9:29	21:01	33	67
SD	9:57	2:30	8:19	9	9

NB. Climbing times are different to Tables 3.4.2 to 3.4.4 due to variation in participant numbers, WT during Climb 1 were wearing a sea survival suit.

Figure 3.4.1 demonstrates that during Climb 1 (exercising + rest) climbers spent significantly ($t_{(14)}$ = –8,8500; p < 0,001; *d* = –4,55) less time metabolising energy aerobically (25 [11] %) than anaerobically (75 [11] %). Climb 2 climbers spent significantly ($t_{(14)}$ = –3,701; p = 0,002; *d* = –1,92) less time metabolising energy aerobically (38 [12] %) than anaerobically (61 [12] %). Climb 3 there was no significant difference ($t_{(14)}$ = –0,358; p = 0,726; *d* = –0,17) in the time spent metabolising energy aerobically (48 [18] %) and anaerobically (51 [18] %). There were no significant differences between WT and novice climbers, WT tended to work more anaerobically (3 %, 8 % and 6 % for each climb respectively), this is likely due to less cumulative rest (*i.e.* Climb 1 = 5 min 33 s; Climb 2 = 6 min 53 s and Climb 3 = 9 min 53 s).

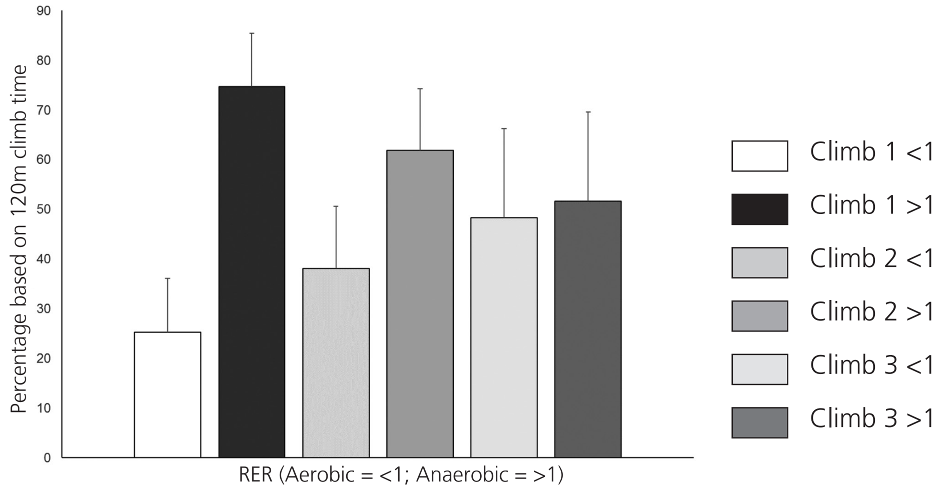


Figure 3.4.1: Mead (SD) Estimated percentage of total time spent metabolising energy aerobically and anaerobically (Climb 1 n = 15 [WT = 6; Novice = 9]; Climb 2, n = 15 [WT = 6; Novice = 9]: Climb 3 n = 14 [WT = 5; Novice = 9]). *NB.* Data could not be computed for one WT due to removal of the facemask between each 30 m climb

Peak Oxygen Consumption

Peak oxygen consumption has been reported as none of the climbers, reached a steady state whilst climbing. Peak oxygen consumptions were either obtained at the end of each 30 m climb or just before a self-selected rest break occurred. There were no significant differences (p > 0,05) in peak oxygen consumption across each 120 m climb (*i.e.* Climb 1, 2 and 3), between each 30 m climb or between climbers (*i.e.* WT vs novices, Table 3.4.6).

Peak oxygen consumption for WT, with the addition of the sea survival suit for Climb 1, was no different than Climbs 2 or 3. Nor did the addition of a sea survival suit alone impair the lighter individuals (Figure 3.4.2). This is likely due to the sea survival suit only adding approximately 2 kg to body weight, whereas the remaining external load, approx. 10 kg has a higher proportion located on the torso and feet. The impact that the external load has on smaller/lighter individuals cannot be determined from these data as individuals were working at different speeds and could self-select to stop during climbs.

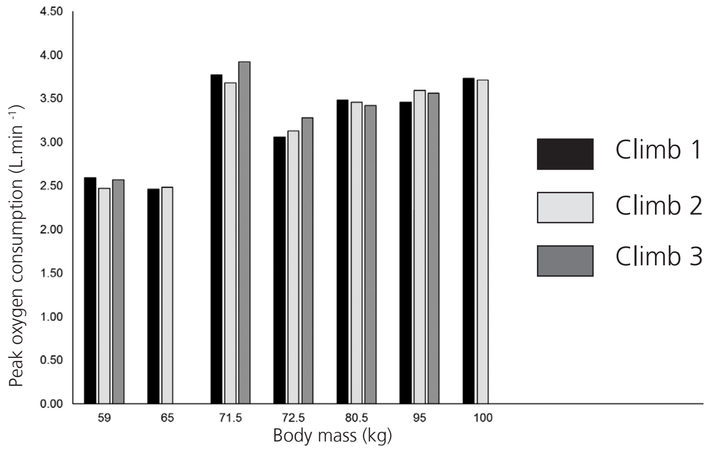


Figure 3.4.2: Peak Oxygen consumption for Wind Technicians across each of the three 120 m climbs. Climb 1 is with the addition of a sea survival suit

Table 3.4.6: Peak oxygen consumption for each 120 m (4 x 30 m climbs) ascent (n = 17 WT n = 7; Male = 5, Female = 2: Novice Climbers n = 10; Male = 9, Female = 1)

		WT			Novice			Combined		
		$L.min^{-1}$	$mL.kg^{-1}.min^{-1}$	% $\dot{V}O_{2max}$*	$L.min^{-1}$	$mL.kg^{-1}.min^{-1}$	% $\dot{V}O_{2max}$*	$L.min^{-1}$	$mL.kg^{-1}.min^{-1}$	% $\dot{V}O_{2max}$*
Climb 1**	Mean	3,05	39,73	76	3,11	37,28	72	3,08	38,30	74
	SD	0,44	5,16	8	0,42	3,69	14	0,48	4,50	12
	Min	2,27	33,6	64	2,24	31,71	49	2,24	31,71	49
	Max	3,77	52,73	94	3,72	47,29	109	3,77	52,73	109
Climb 2	Mean	3,02	39,25	75	^3,09	^38,05	74	^3,06	^38,57	74
	SD	0,53	5,28	9	0,35	5,68	13	0,53	5,50	11
	Min	2	32,62	62	2,43	26,15	54	2	26,15	54
	Max	3,71	51,47	92	3,68	51,14	104	3,71	51,47	104
Climb 3	Mean	^^3,17	^^42,32	78	^^3,13	^^37,77	69	^^3,15	^^39,40	73
	SD	0,45	5,96	12	0,32	4,80	9	0,37	5,64	11
	Min	2,44	30,10	66	2,47	28,59	54	2,44	28,59	54
	Max	3,92	54,83	98	3,81	46,71	87	3,92	54,83	98

* % $\dot{V}O_{2max}$ is calculated based on the maximum oxygen uptake scores predicted from the Chester step test. 104
** This climb was undertaken with the addition of a sea survival suit
^ n = 16; novice climbers = 9
^^ n = 14; WT = 6; novice climbers = 9

Heart rate training zones
To provide an insight into the physical demand of ascending a 120 m vertical ladder, HR data were categorised into zones (Table 3.4.7). Calculations were based on the cumulative time spent climbing and resting (Table 3.4.5). The data are presented as a percentage of this cumulative time.

Table 3.4.7: Heart rate zones

Heart Zone	Percentage heart rate maximum*	Work intensity
Z1	Less than 50	Very Very light
Z2	50 to 60	Very light
Z3	60 to 70	Light
Z4	70 to 80	Moderate
Z5	80 to 90	Hard
Z6	90 to 100	Maximum

* Heart rate maximums were derived from age predicted max (220 – age)

There were no significant differences across the three climbs in terms of the times spent in each HR zone. Significant differences were observed with respect to the times spent in each of the HR zones (Table 3.4.8 to 3.4.10). Given that approximately 2/3 of the time was spent resting climbers spent on average less than 10 % of the time in Zone 1, suggesting that the exercise was physically demanding and with the majority of the rest time spent recovering.

Table 3.4.8: Significant differences between mean (SD) time spent in each of the heart rate zones for Climb 1 (n = 17; WT n = 7; Male = 5, Female = 2: Novice Climbers n = 10; Male = 9, Female = 1)

Comparison				*t* Statistic	df	p	Effect Size
	Zone	Mean % time spent in each HR zone	SD				
1	Z1	10,00	11,69	–2,292	15	0,037	–0,70
	Z2	17,75	11,13				
3	Z1	10,00	11,69	–3,357	15	0,004	–1,12
	Z4	21,69	9,09				
4	Z1	10,00	11,69	–2,616	15	0,019	–1,10
	Z5	22,06	10,12				
5	Z4	21,69	9,09	2,272	15	0,038	0,88
	Z6	10,94	14,75				
6	Z5	22,06	10,12	2,346	15	0,033	0,88
	Z6	10,94	14,75				

Table 3.4.9: Significant differences between mean (SD) time spent in each of the heart rate zones for Climb 2 (n = 17; WT n = 7; Male = 5, Female = 2: Novice Climbers n = 10; Male = 9, Female = 1)

Comparison				*t* Statistic	df	p	Effect Size
	Zone	Mean % time spent in each HR zone	SD				
1	Z1	10,29	13,61	–3,155	16	0,006	–1,11
	Z4	22,11	6,54				
2	Z1	10,29	13,61	–2,612	16	0,019	–1,07
	Z5	23,29	10,61				
3	Z3	16,06	7,56	–2,214	16	0,042	–0,86
	Z4	22,11	6,54				
4	Z3	16,06	7,56	–2,478	16	0,025	–0,78
	Z5	23,29	10,61				
5	Z3	16,06	7,56	2,230	16	0,040	0,58
	Z6	9,94	12,99				
6	Z4	22,12	6,54	3,004	16	0,008	1,18
	Z6	9,94	12,99				
7	Z5	23,29	10,61	3,414	16	0,004	1,13
	Z6	9,94	12,99				

Table 3.4.10: Significant differences between mean (SD) time spent in each of the heart rate zones for Climb 3 (n = 17; WT n = 7; Male = 5, Female = 2: Novice Climbers n = 10; Male = 9, Female = 1)

Comparison				*t* Statistic	df	p	Effect Size
	Zone	Mean % time spent in each HR zone	SD				
1	Z1	5,73	7,74	–4,228	14	0,001	–1,13
	Z2	19,13	14,80				
2	Z1	5,73	7,74	–3,845	14	0,002	–1,68
	Z3	19,27	8,37				
3	Z1	5,73	7,74	–5,796	14	<0,001	–2,14
	Z4	21,53	7,01				
4	Z1	5,73	7,74	–4,637	14	<0,001	–1,93
	Z5	20,40	7,44				

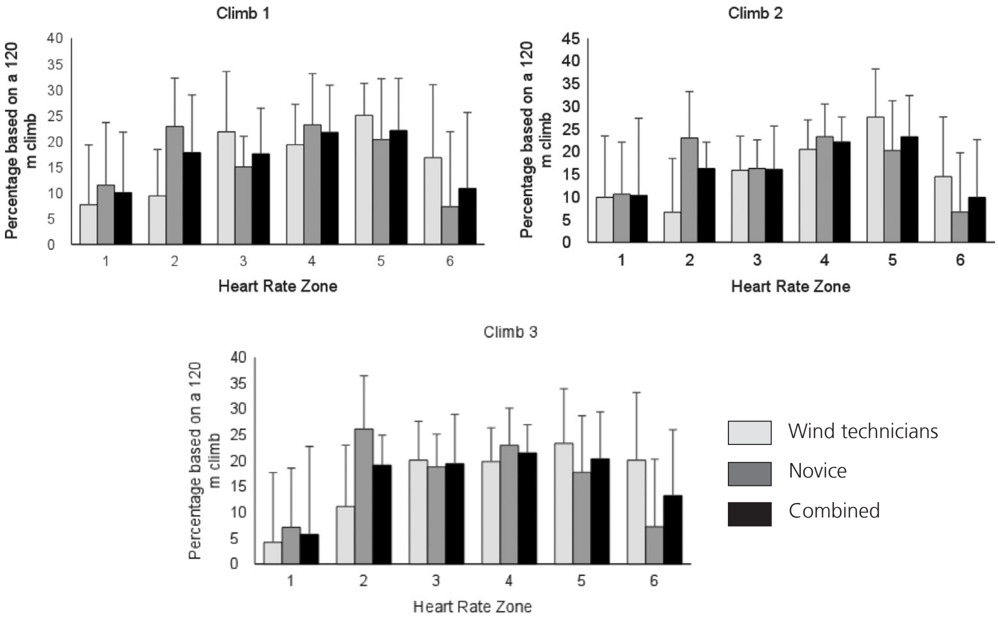


Figure 3.4.3: Mean (SD) percentage of total time spent in each heart rate zone. Climb 1, n = 17 (WT = 7; Novice = 10); Climb 2, n = 17 (WT = 7; Novice = 10); Climb 3, n = 15 (WT = 7; Novice = 8)

Peak Heart Rate

There were no significant differences in peak HR when presented as a percentage of age predicted HR maximum (PHRM), across the three climbs (Table 3.4.11). WT demonstrated significantly higher PHRM for each of the three climbs when compared to the novice climbers (Table 3.4.11 and 3.4.12). The higher PHRM observed is likely due to faster climbing rates and less rest.

Table 3.4.11: Peak percentage of predicted heart rate maximum (PHRM) for each 120 m (4 x 30 m climbs) ascent (n = 17; WT n = 7; Male = 5, Female = 2: Novice Climbers n = 10; Male = 9, Female = 1)

		WT*	Novice Climbers	Combined
Climb 1 (% PHRM)	Mean	94	87	90
	SD	4	5	6
	Min	87	80	80
	Max	99	98	99
Climb 2 (% PHRM)	Mean	93	87	90
	SD	6	6	6
	Min	85	80	80
	Max	101	98	101
Climb 3 (% PHRM)	Mean	94	80	86
	SD	5	16	15
	Min	86	44	44
	Max	100	98	100

* This climb was undertaken with the addition of a sea survival suit

Table 3.4.12: Significant differences in percentage of age predicted heart rate maximum between Wind Technicians and Novices (n = 16; WT n = 7; Novice Climbers n = 9)

Comparison		*t* Statistic	df		p	Effect Size
Climb	**Zone**					
Climb 1	WT	–2,553	15		0,022	1,55
	Novice					
Climb 2	WT	–2,250	15		0,040	1,00
	Novice					
Climb 3	WT	–2,200	15		0,044	1,18
	Novice					

Blood Lactate
Post climb blood lactates ranged from low (2,4 $mmol.L^{-1}$) to high (11,9 $mmol.L^{-1}$) depending on the individual. The highest and lowest blood lactates reported across each of the three climbs were by WT; these two climbers were the only two not to take a self-selected rest during any of the climbs.

Delta changes in blood lactate, irrespective of climbing experience, was significantly different across climbs ($F_{(2,30)}$ = 6,453; p = 0,002). With Climb 1 reporting significantly higher delta change than both Climb 2 ($t_{(15)}$ = 3,312; p = 0,005; *d* = –0,69) and Climb 3 ($t_{(15)}$ = 2,944; p = 0,010; *d* = –0,67). Blood lactates returning to resting levels before the start of each climb. There was no significant difference in blood lactates between Climbs 2 and 3. Based on the mean blood lactate data, WT change was 2 $mmol.L^{-1}$ (Climb 1; *d* = 0,84; *NB:* WT had the addition of a sea survival suit), 2 $mmol.L^{-1}$ (Climb 2; *d* = 0,72), and 1,7 $mmol.L^{-1}$ (Climb 3; *d* = 0,54) higher than the novice climbers (Tables 3.4.2 to 3.4.4). These changes in blood lactate from pre to post climbing indicated that WT were working harder with the addition of the sea survival suit, but also harder than the novice climbers, likely due shorter faster climbs with a reduction in rest (Table 3.4.13).

Table 3.4.13: Delta change in blood lactate pre and post 120 m (4 x 30 m climbs) ascent (WT n = 5; Male = 3, Female = 2: Novice Climbers n = 10; Male = 9, Female = 1)0

		WT*	Novice Climbers	Combined
Climb 1 (delta change in $mmol.L^{-1}$)	Mean	7,40	5,40**	6,30***
	SD	3,00	1,50	2,40
	Min	1,70	2,20	1,70
	Max	10,50	7,00	10,50
Climb 2 (delta change in $mmol.L^{-1}$)	Mean	5,70	3,70	4,50
	SD	3,10	2,40	2,80
	Min	1,20	1,00	1,00
	Max	10,10	8,00	10,10

Table 3.4.13: Delta change in blood lactate pre and post 120 m (4 x 30 m climbs) ascent (WT n = 5; Male = 3, Female = 2: Novice Climbers n = 10; Male = 9, Female = 1)0 (continued)

		WT*	Novice Climbers	Combined
Climb 3 (delta change in mmol.L^{-1})	Mean	5,40	3,70	4,40
	SD	3,20	3,10	3,20
	Min	0,70	0,30	0,30
	Max	10,80	7,00	10,80

* This climb was undertaken with the addition of a sea survival suit
*** n = 9 (8 males; 1 female)*
**** n = 16 (13 males; 3 females)*

<u>*Grip Strength and Endurance*</u>

Grip Strength
Following each climb a large and significant decrement in grip strength, of both hands, was observed in the WT and novice climbers (Tables 3.4.14 and 3.4.15). Grip strength remained significantly lowered at the start of the second and third climbs compared to the first (Tables 3.4.14 and 3.4.15). There were no significant differences between grip strength at the start of the second and third climbs (Tables 3.4.14). There were no difference between WT and novice climbers (Table 3.4.14). On completion of the third ladder climb by WT grip strength scores had fallen to 57 % of baseline values, for the left hand, and 62 %, for the right hand. The corresponding data for novice climbers grip strength on completion of the third ladder climb were 52 %, for the left hand, and 54 %, for the right hand. This demonstrates a significant loss in grip strength as a result of three 120 m climbs.

Table 3.4.14: Grip Strength pre and post each 120 m climb. (n = 17; WT n = 7; Male = 5, Female = 2: Novice Climbers n = 10; Male = 9, Female = 1)

		WT		Novice Climbers		Combined	
		Left	**Right**	**Left**	**Right**	**Left**	**Right**
Pre Climb 1 (kg)	Mean	39,09	40,54	43,74	44,45	41,82	42,84
	SD	6,69	8,73	7,40	7,73	7,29	8,13
	Min	29,30	28,30	35,80	35,50	29,30	28,30
	Max	46,60	53,50	59,60	61,70	59,60	61,70
Post Climb 1 (kg)	Mean	23,03	26,76	25,80	25,83	24,66	26,21
	SD	5,90	7,67	6,56	5,35	6,26	6,20
	Min	17,10	18,50	15,10	16,80	15,10	16,80
	Max	32,00	38,00	34,00	35,10	34,00	38,00
Change Climb 1 (kg)	Mean	16,06	13,76	17,94	18,62	17,16	16,63
	SD	4,36	4,17	5,75	6,60	5,16	6,08
Pre Climb 2 (kg)	Mean	34,04	36,69	33,81	37,15	33,91	36,96
	SD	4,19	6,97	9,42	10,07	7,52	8,68
	Min	27,00	25,40	21,30	23,60	21,30	23,60
	Max	37,30	47,40	50,60	53,80	50,60	53,80

Table 3.4.14: Grip Strength pre and post each 120 m climb. (n = 17; WT n = 7; Male = 5, Female = 2: Novice Climbers n = 10; Male = 9, Female = 1) (continued)

		WT		Novice Climbers		Combined	
		Left	**Right**	**Left**	**Right**	**Left**	**Right**
Post Climb 2 (kg)	Mean	23,49	26,63	23,87	25,44	23,71	25,93
	SD	4,90	6,99	7,96	6,89	6,68	6,74
	Min	19,50	20,60	16,70	16,50	16,70	16,50
	Max	33,10	39,90	38,70	39,50	38,70	39,90
Change Climb 2 (kg)	Mean	10,56	10,06	9,94	11,71	10,19	11,03
	SD	5,12	3,97	5,38	7,52	5,12	6,20
Pre Climb 3 (kg)	Mean	35,20	36,40	33,85	36,62	34,41	36,53
	SD	5,51	7,58	7,51	7,65	6,60	7,38
	Min	27,10	25,90	22,40	24,70	22,40	24,70
	Max	41,70	48,40	46,50	51,80	46,50	51,80
Post Climb 3 (kg)	Mean	22,14	25,29	22,71	24,12	22,46	24,63
	SD	6,88	6,67	7,10	7,50	6,77	6,94
	Min	14,90	18,10	14,80	15,20	14,80	15,20
	Max	36,40	38,40	34,90	39,40	36,40	39,40
Change Climb 3 (kg)	Mean	13,06	11,11	13,41	14,91	13,26	13,35
	SD	4,77	5,59	8,93	10,96	7,31	9,11

Table 3.4.15: Statistical analysis of grip strength

	Left hand				**Right hand**			
Difference between climbs	$F_{(2,30)}$ = 11,920; p < 0,001				$F_{(2,30)}$ = 15,059; p < 0,001			
Difference between time (pre and post climbs)	$F_{(1,15)}$ = 269,966; p < 0,001				$F_{(1,15)}$ = 151,576; p < 0,001			
Interaction effect between climbs and time	$F_{(2,30)}$ = 10,984; p < 0,001				$F_{(2,30)}$ = 5,945; p = 0,007			
Post hoc analysis	***t***	**df**	**p**	**Effect Size**	***t***	**df**	**p**	**Effect Size**
Climb 1 Pre Vs Climb 2 Pre	4,828	16	<0,001	1,07	4,092	16	0,001	0,7
Climb 1 Pre Vs Climb 1 Post	13,710	16	<0,001	2,53	–11,269	16	<0,001	2,30
Climb 2 Pre Vs Climb 2 Post	8,210	16	<0,001	1,43	7,335	16	<0,001	1,37
Climb 3 Pre Vs Climb 3 Post	10,279	15	<0,001	1,79	8,722	15	<0,001	1,66

Grip Endurance

As with grip strength, following each climb a large and significant decrement in grip endurance, of both hands, was observed in the WT and novice climbers (Tables 3.4.16 and 3.4.17). Grip endurance remained significantly lowered at the start of the second and third climb compared to the first (Tables 3.4.16 and 3.4.17). There were no significant differences between grip endurance at the start of the second and third climb (Tables 3.4.16).

Table 3.4.16: Mean (SD) Grip Endurance during the final 18 s of a 30 s test, pre and post each 120 m climb. (WT n = 7; Male = 5, Female = 2: Novice Climbers n = 10; Male = 9, Female = 1)

		WT		Novice Climbers		Combined	
		Left	**Right**	**Left**	**Right**	**Left**	**Right**
Pre climb 1 (kg)	Mean	26,07	25,24	25,89	23,55	25,96	24,25
	SD	5,02	4,20	5,30	5,37	5,03	4,85
	Min	17,00	18,50	19,10	13,40	17,00	13,40
	Max	30,90	30,60	33,30	31,20	33,30	31,20
Post climb 1 (kg)	Mean	18,61	18,44	16,16	15,90	17,17	16,95
	SD	5,49	4,49	3,87	4,61	4,61	4,60
	Min	12,10	12,50	11,00	9,10	11,00	9,10
	Max	26,29	21,10	22,80	26,10	26,29	26,10
Change Climb 1 (kg)	Mean	7,46	6,80	9,73	7,65	8,79	7,30
	SD	3,09	4,13	5,34	6,49	4,57	5,50
Pre Climb 2 (kg)	Mean	24,09	22,69	18,16	18,68	20,60	20,33
	SD	5,34	4,51	4,94	6,61	5,78	6,03
	Min	15,90	16,10	11,50	9,50	11,50	9,50
	Max	31,90	28,60	29,40	34,00	31,90	34,00
Post Climb 2 (kg)	Mean	18,54	16,71	14,36	13,69	16,08	14,94
	SD	5,24	3,95	2,93	3,36	4,43	3,82
	Min	10,10	11,50	10,20	9,50	10,10	9,50
	Max	21,10	19,10	20,00	19,10	26,70	23,50
Change climb 2 (kg)	Mean	4,54	4,86	3,80	4,99	4,11	4,94
	SD	1,17	1,96	4,85	5,03	3,72	3,96
Pre Climb 3 (kg)	Mean	22,00	20,96	17,93	17,83	19,61	19,12
	SD	5,13	3,96	5,88	5,12	5,79	4,81
	Min	15,20	16,30	11,00	10,70	11,00	10,70
	Max	27,90	26,90	32,20	27,50	32,20	27,50
Post Climb 3 (kg)	Mean	17,99	16,74	13,25	13,34	15,20	14,74
	SD	4,29	3,93	2,81	3,70	4,14	4,06
	Min	11,80	11,70	9,50	7,60	9,50	7,60
	Max	22,40	21,10	19,00	20,00	22,40	21,10
Change climb 3 (kg)	Mean	4,01	4,21	4,68	4,49	4,41	4,38
	SD	3,25	3,01	6,00	4,82	4,93	4,06

Table 3.4.17: Statistical analysis of grip endurance

	Left hand				Right hand			
Difference between climbs	$F_{(2,32)}$ = 19,316; p < 0,001				$F_{(2,32)}$ = 19,951; p < 0,001			
Difference between time (pre and post climbs)	$F_{(1,16)}$ = 61,572; p < 0,001				$F_{(1,16)}$ = 70,978; p < 0,001			
Interaction between climb and time	$F_{(1,497,23,945)}$ = 6,451; p = 0,010				Not significant			
Post hoc analysis	***t***	**df**	**p**	**Effect Size**	***t***	**df**	**p**	**Effect Size**
Climb 1 Pre Vs Climb 2 Pre	4,418	16	<0,001	0,99	2,675	16	0,017	0,72
Climb 1 Pre Vs Climb 1 Post	7,928	16	<0,001	1,82	–5,469	16	<0,001	1,54
Climb 2 Pre Vs Climb 2 Post	4,564	16	<0,001	0,88	.5,548	16	<0,001	1,07
Climb 3 Pre Vs Climb 3 Post	3,684	16	0,002	0,83	4,443	16	<0,001	0,98

Manual Dexterity

On average it took participants 23 % longer to tighten the nuts and screws than loosen them (Table 3.4.18). Between climbs there were significant differences in the times take to undo and tighten the nuts and screws and subsequently total time (Tables 3.4.18 to 3.4.21). These differences showed that individuals became significantly faster before undertaking each climb and after each climb (Tables 3.4.18 to 3.4.21). Climbs 1 and 2 did not result in a significant difference pre and post climb, whereas Climb 3 showed climbers to be faster on the test post climb compared to pre climb, but only when tightening the nuts and screws (Table 3.4.19 to 3.4.21). Examining the individual data for each climb; 7 participants (n = 3 WT; n = 4 novices) following Climb 1; 6 participants (n = 2 WT; n = 4 novices) following Climb 2, and 5 participants (n = 2 WT; n = 3 novices) following Climb 3 demonstrated slower times post to pre. There were no differences between WT and novice climbers except for on the first attempt where WT were on average 1 min 7 s (d = –1,15) faster than the novice climbers.

Table 3.4.18: Manual dexterity times pre and post each 120 m (4 x 30 m climbs) (WT n = 7; Male = 5, Female = 2: Novice Climbers n = 10; Male = 9, Female = 1)

		WT	Novice Climbers	Combined
Pre Climb 1 (min:s)	Mean	7:54	9:01	8:31
	SD	1:21	1:35	1:32
	Min	6:16	6:31	6:16
	Max	10:14	12:19	12:19

Table 3.4.18: Manual dexterity times pre and post each 120 m (4 x 30 m climbs) (WT n = 7; Male = 5, Female = 2: Novice Climbers n = 10; Male = 9, Female = 1) (continued)

		WT	Novice Climbers	Combined
Post Climb 1 (min:s)	Mean	7:55	8:44	8:23
	SD	1:42	1:26	1:33
	Min	5:57	6:51	5:57
	Max	10:09	11:39	11:39
Pre Climb 2 (min:s)	Mean	7:35	7:58	7:48
	SD	2:02	1:04	1:29
	Min	5:22	6:44	5:22
	Max	11:14	9:43	11:14
Post Climb 2 (min:s)	Mean	7:04	7:39	7:24
	SD	2:01	0:58	1:28
	Min	4:30	5:55	4:30
	Max	9:35	9:04	9:35
Pre Climb 3 (min:s)	Mean	7:04	7:51	7:22
	SD	2:02	1:08	1:32
	Min	4:47	6:01	4:47
	Max	9:51	9:36	9:47
Post Climb 3 (min:s)	Mean	6:57	7:16	7:00
	SD	1:53	1:12	1:30
	Min	4:53	5:54	4:13
	Max	9:20	9:55	9:45

Table 3.4.19: Statistical analysis of the time taken to undo the nuts and screws

	Undoing the nuts and screws			
Difference between climbs	$F_{(2,32)}$ = 12,391; p < 0,001			
Post hoc analysis	***t***	**df**	**p**	**Effect Size**
Climb 1 Pre Vs Climb 3 Pre	3,016	15	0,09	0,39
Climb 1 Post Vs Climb 3 Post	3,012	15	0,08	0,72

Table 3.4.20: Statistical analysis of the time taken to tighten the nuts and screws

	Tightening the nuts and screws			
Difference between climbs	$F_{(1,439,21,588)}$ = 12,625; p = 0,001			
Difference between time (pre and post climbs)	$F_{(1,15)}$ = 5,590; p = 0,032			
Post hoc analysis	***t***	**df**	**p**	**Effect Size**
Climb 1 Pre Vs Climb 2 Pre	2,698	15	0,017	0,47
Climb 1 Pre Vs Climb 3 Pre	3,321	15	0,005	0,71
Climb 1 Post Vs Climb 2 Post	3,545	16	0,003	0,62
Climb 1 Post Vs Climb 3 Post	4,061	16	0,001	0,91
Climb 2 Post Vs Climb 3 Post	3,039	16	0,008	0,34

Table 3.4.21: Statistical analysis of the total time to undertake the manual dexterity task

	Total time			
Difference between climbs	$F_{(1,417,22,673)}$ = 20,283; p < 0,001			
Difference between time (pre and post climbs)	$F_{(1,16)}$ = 9,671; p < 0,001			
Post hoc analysis	***t***	**df**	**p**	**Effect Size**
Climb 1 Pre Vs Climb 2 Pre	3,261	16	0,005	0,49
Climb 1 Pre Vs Climb 3 Pre	3,328	16	0,004	0,77
Climb 2 Pre Vs Climb 3 Pre	2,193	16	0,043	0,29
Climb 1 Post Vs Climb 2 Post	4,149	16	0,001	0,65
Climb 1 Post Vs Climb 3 Post	4,924	16	<0,001	0,91
Climb 2 Post Vs Climb 3 Post	2,899	16	,010	0,27

Kinematic

Four kinematic variables are presented in this report (Tables 3.4.22 and 3.4.23). The first variable represents the clearance between the toe marker and the rungs of the ladder. A significant difference was found in the toe clearance ($F_{(2,30)}$ = 6,278; p = 0,002) over the three climbs, irrespective of experience, indicating that the distance between the toe and the rungs of the ladder significantly decreased as the climb number increased. Toe clearance during Climb 2 was significantly ($t_{(16)}$ = –2,711, p < 0,01, *d* =1,08) less than Climb 1. Toe clearance during Climb 3 was significantly ($t_{(16)}$ = –3,160, < 0,01, *d* =1,51) less than Climb 1. No significant difference was found between Climbs 2 and 3 (Table 3.4.22). A significant difference was found between the two groups ($F_{(2,30)}$ = 6,453; p = 0,002) with the technicians having a significantly greater toe clearance than the novices in Climb 1. Further analysis showed that WT had significantly ($t_{(16)}$ = –1,990, p = 0,023, *d* = 1,17) greater toe clearance during Climb 1 than the novice climbers. No significant difference were found between WT and novice climber for climbs 2 and 3 (Table 3.4.22).

Ankle angle at contact reflects the position of the foot as it makes contact with the ladder during climbing. No significant ($F_{(2,30)}$ = 1,002; p > 0,05) differences between climbs were found. Mean (SD) data for both groups decreased after the first climb with similar values found for Climb 2 and Climb 3. Visual inspection of the data indicates that there were large variations both within and between participants in each group. This has led to large standard deviations across all conditions. Effect size calculations were carried out between the groups at each climb (Climb 1: *d* = –0,67; climb 2: *d* = –0,36 and climb 3: *d* = –0,3). This shows that none of the participants changed their foot angle as they stepped onto the ladder regardless of the groups they were in, or the climb that they were completing (Table 3.4.22).

Mean hip range of Motion (ROM) displays the use of the stronger lower limb muscles around the hip joint in climbing. WT used a significantly ($F_{(2,30)}$ = –3,572 p = 0,005) greater range of motion, thus used the lower limbs more during the climbs than the novice climbers. This difference between the two groups was evident in all three climbs Climb 1 ($t_{(16)}$ = –2,211, p = 0,011, *d* = –1,63), Climb 2 ($t_{(16)}$ = –3,538, p = 0,001, *d* = –2,42) and Climb 3 ($t_{(16)}$ = –3,677, p < 0,001, *d* = –4,08). Despite the increased fatigue, the WT did not change their hip range of motion between the climbs and were able to maintain the use of these large muscles of the lower limbs. The novice climbers reduced the hip range of motion from Climb 1 to Climb 2 and again to Climb 3 indicating that upper body limbs were used to a greater extent in the latter climbs (Table 3.4.22).

Peak shoulder flexion reflects the reach of the arms during climbing. A significant ($F_{(2,30)}$ = 3,726; p = 0,001) difference, irrespective of experience, was found between the three climbs. Significantly ($t_{(16)}$ = –6,643; p < 0,001, d = –1,47) greater shoulder flexion was found in Climb 2 compared to Climb 1 and in Climb 3 compared to Climb 1 ($t_{(16)}$ = –7,643; p < 0,001; d = –1,89). No significant difference was found between Climb 2 and Climb 3. WT demonstrated significantly ($t_{(16)}$ = 4,09; p = 0,001, d = 1,01) less shoulder flexion during Climb 1 than novice climbers. There were no differences in climbs 2 and 3 (Table 3.4.23).

Table 3.4.22: Mean (SD) foot angle at contact during each 120 m climb. (n = 17; WT n = 7; Male = 5, Female = 2: Novice Climbers n = 10; Male = 9, Female = 1)

		Mean (SD) Toe Clearance (m)	Mean (SD) Ankle angle at contact (^{0})
Climb 1	WT*	0,054 (0,005)	86 (12,8)
	Novice	0,049 (0,0037)	78 (10,2)
Climb 2	WT	0,049 (0,004)	78 (9,9)
	Novice	0,047 (0,0035)	74 (11,6)
Climb 3	WT	0,048 (0,005)	76 (8,5)
	Novice	0,044 (0,0033)	76 (12,3)

The data presented represents a 30 second excerpt from the trial.
* This climb was undertaken with the addition of a sea survival suit

Table 3.4.23: Mean (SD) kinematic data during each 120 m climb. (n = 17; WT n = 7; Male = 5, Female = 2: Novice Climbers n = 10; Male = 9, Female = 1)

		Mean (SD) Hip ROM(^{0})	Mean (SD) Peak Shoulder Flexion (^{0})
Climb 1	WT*	59 (5,5)	113 (8,3)
	Novice	51 (3,8)	122 (9,2)
Climb 2	WT	56 (4,5)	132 (9,7)
	Novice	46 (3,5)	133 (10,1)
Climb 3	WT	59 (4,7)	134 (9,6)
	Novice	42 (3,2)	138 (10,4)

The data presented represents a 30 second excerpt from the trial.
* This climb was undertaken with the addition of a sea survival suit

Kinematic Data During the Descent
Following each of the 120 m climbs, climbers completed three ascents and descents of the ladder in a fixed position. Toe clearance was calculated and compared between the ascent and descent. Although differences in the mean data can be seen (Table 3.4.24), no significant differences (p > 0,05) can be seen between the data from the ascent and the descent. It can be seen that the standard deviations of the descent are very large. This may be due to the short nature of the climb. With only 3 to 4 steps to get from the top of the ladder to the bottom of the ladder, the climbers may not have found a rhythm in the climbing pattern. Longer distance descent may be required to further evaluate toe clearance data during descent.

Table 3.4.24: Mean (SD) toe clearance during each 120 m climb and descent. (n = 17; WT n = 7; Male = 5, Female = 2: Novice Climbers n = 10; Male = 9, Female = 1)

		Mean (SD) Toe Clearance during ascent (m)	Mean (SD) Toe Clearance during descent (m)
Climb 1	WT*	0,054 (0,005)	0,045 (0,049)
	Novice	0,049 (0,0037)	0,041 (0,029)
Climb 2	WT	0,049 (0,004)	0,051 (0,024)
	Novice	0,047 (0,0035)	0,051 (0,0085)
Climb 3	WT	0,048 (0,005)	0,052 (0,078)
	Novice	0,044 (0,0033)	0,045 (0,011)

The data presented represents a 30 second excerpt from the trial.
* This climb was undertaken with the addition of a sea survival suit

<u>Kinetic</u>
Table 3.4.25 details the mean (SD) peak muscle activation, as measured by EMG, for each climb. This value is a representation throughout the climbing period and is not individualised to each hand or foot movement.

A significant ($F_{(2,30)}$ = –3,028, p = 0,02) difference in forearm muscle activation, irrespective of experience, was found between climbs. Higher levels of forearm muscle activation were found for Climb 2 compared to Climb 1 ($t_{(16)}$ = –3,011, p = 0,011, d = –1,4) and again between in Climb 3 compared to Climb 1 ($t_{(16)}$ = –3,844, p < 0,001, d = –2,75). No differences were found between climbs 2 and 3. This difference was attributed to the novice climbers, as they demonstrated significantly ($t_{(16)}$ = –2,016, p = 0,004, d = –2,74) higher forearm muscle activation in Climb 2 and Climb 3 ($t_{(16)}$ = –2,011, p = 0,023, d = –1,32) compared to the WT. No significant differences were found for Climb 1. This shows that both groups used the forearm muscles to a similar extent in the first climb, but during the second climb and third climb the novice group used the forearm muscles to a greater extent (Table 3.4.25).

A significant ($F_{(2,30)}$ = –2,678, p = 0,045) difference, irrespective of experience, was found between climbs for bicep muscle activation. Higher levels of bicep muscle activation were found for Climb 3 compared to Climb 1 ($t_{(16)}$ = –3,611, p < 0,001, d = –2,21) and again between Climb 2 and Climb 3 ($t_{(16)}$ = –3,277, p < 0,001, d = –2,15). No significant difference was found between Climb 1 and Climb 2. Novice Climbers showed significantly ($t_{(16)}$ = –2,016, p = 0,013, d = –1,22) higher muscle activation in the bicep during Climb 3. No significant differences between the groups were found for climbs 1 and 2. This shows that the change in use of the bicep muscle group occurred in the third climb with a significant increase from the previous two climbs and with the novice climbers using the muscle to a greater extent than the WT (Table 3.4.25).

A significant ($F_{(2,30)}$ = –3,702, p < 0,001) difference, irrespective of experience, was found between climbs for muscle activation in the anterior deltoid. Higher levels of anterior deltoid muscle activation were found for Climb 2 compared to Climb 1 ($t_{(16)}$ = –1,911, p = 0,021, d = –2,766) and again between in Climb 3 compared to Climb 1 (p < 0,001). ($t_{(16)}$ = –3,011, p < 0,001, d = –1,4). This shows that both groups of participant relied on this muscle group to a greater extent as the climbs continued. Novice climbers demonstrated a significantly greater anterior deltoid muscle activation than the WT during Climb 1 ($t_{(16)}$ = –1,811, p = 0,031, d = –1,40), Climb 2 ($t_{(16)}$ = –2,461, p = 0,042, d = –3,90) and Climb 3 ($t_{(16)}$ = –2,411, p = 0,038, d = 2,13). This shows that the WT used this muscle less in all three climbs.

No significant differences were found for the calf muscle group activation across each of the climbs. Visual inspection of these data suggesting increases for both groups across each of the climbs, however, there were large standard deviations for both groups in all climbs. This variability between participants was evident in the calf muscle groups to a much greater extent than any of the other muscle groups.

The data gathered suggest that WT experienced greater fatigue in the calf muscle when compared to the novices, whilst the novices experienced greater fatigue in the upper body. This supports the kinematic data that suggested WT climb ladders using the larger muscles of the lower limbs, whilst novice climbers rely more on the small muscle of the upper body.

Table 3.4.25: Mean (SD) kinetic data (EMG) during each 120 m climb. (n = 17; WT n = 5; Male = 3, Female = 2: Novice Climbers n = 5; Male = 4, Female = 1)

		Forearm	Bicep	Anterior Deltoid	Calf
Climb 1	WT*	51 (5,2)	48 (4,9)	34 (4,2)	48 (7,8)
	Novice	55 (4,8)	52 (4,65)	46 (4,2)	33 (8,5)
Climb 2	WT	53 (4,9)	48 (4,5)	37 (3,5)	51 (9,8)
	Novice	68 (5,8)	50 (4,5)	53 (4,7)	38 (8,1)
Climb 3	WT	66 (9,4)	61 (9,5)	47 (8,3)	62 (9,6)
	Novice	78 (8,6)	72 (9,1)	66 (9,7)	46 (8,7)

* This climb was undertaken with the addition of a sea survival suit

<u>Perceptual</u>
RPE was found to increase significantly within each 120 m climb, *i.e.* the first 30 m were perceived to be the easiest followed by the 2nd, 3rd and 4th (except on Climb 1 between 60 m and 90 m; Figure 3.4 4 and Table 3.4.26). This pattern was observed in each climb with there being no significant differences ($X^2_{(2,14)}$ = 1,240; p = 0,538) across the three 120 m climbs. There was very little difference between the RPE scores of the WT and novice climbers. This meant individuals climbing the ladder irrespective of climbing duration and speed rated ladder climbing between 'Hard' and 'Very hard', with some participants rating the work as 'Fairly light' while others rated it as 'Very very hard'.

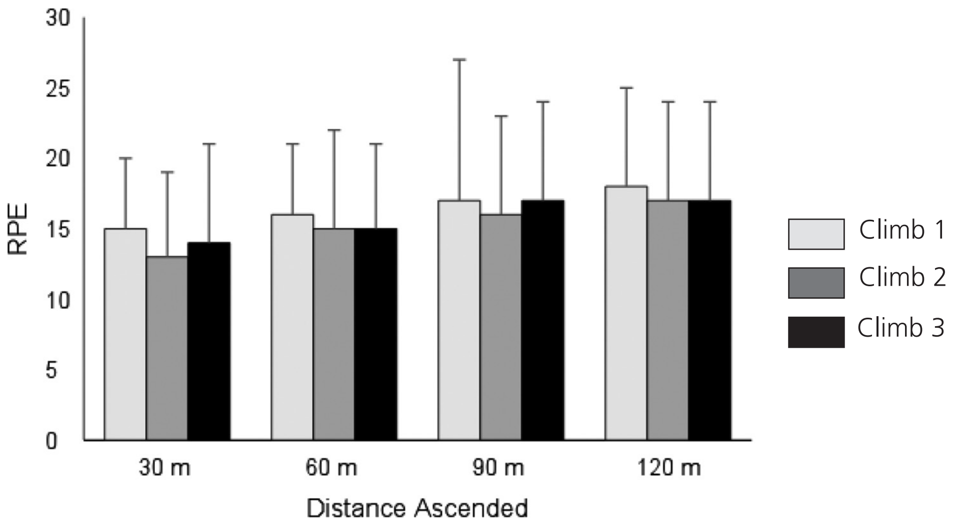


Figure 3.4.4: Mean (SD) RPE across each 30 m climb for each of the three 120 m climbs. (WT n = 7; Male = 5, Female = 2: Novice Climbers n = 10; Male = 9, Female = 1)

Table 3.4.26: Statistical analysis of RPE

Comparison	Z score	df	p	Effect Size
Climb 1 30 m to 60 m	–3,095	16	0,002	–0,75
Climb 1 90 m to 120 m	–3,025	16	0,002	–0,73
Climb 2 30 m to 60 m	–3,596	16	<0,001	–0,87
Climb 2 60 m to 90 m	–2,949	16	0,003	–0,72
Climb 2 90 m to 120 m	–2,521	16	0,012	–0,61
Climb 3 30 m to 60 m	–3,555	16	<0,001	–0,86
Climb 3 60 m to 90 m	–2,516	16	0,012	–0,61
Climb 3 90 m to 120 m	–2,121	16	0,034	–0,51

Correlations

To gain an idea of what might be predicting ladder climbing performance; correlation analysis was performed on the data. It should be noted that the number of participants is low for this type of analysis, but it may inform future research. All of the correlations reported are moderate (Tables 3.4.27 and 3.4.28). These data suggest those individuals who are heavier with a higher sum of skinfolds (*i.e.* higher levels of body fat) will take longer to complete 120 m ladder climb and take longer rests during the climb, with a higher number of rest breaks needed. $\dot{V}O_{2max}$ as predicted by the Chester step test suggested that individuals with a lower aerobic capacity would require longer rests.

Table 3.4.27: Spearman's correlations (n = 17; WT n = 7; Male = 5, Female = 2: Novice Climbers n = 10; Male = 9, Female = 1)

		Climb 1 No. of rests	Climb 2 No. of rests	Climb 3 No. of rests
Mass (kg)	Correlation Coefficient	0,397	0,420	,566*
	Sig. (2-tailed)	0,114	0,093	0,018
	N	17	17	17
Skinfolds (mm)	Correlation Coefficient	0,469	,572*	,609*
	Sig. (2-tailed)	0,067	0,021	0,012
	N	16	16	16

* Correlation is significant at the 0,05 level (2-tailed)

Table 3.4.28: Pearson's correlations (n = 17; WT n = 7; Male = 5, Female = 2: Novice Climbers n = 10; Male = 9, Female = 1)

		Climb 1 Total Time	Climb 1 Rest Time	Climb 1 Time Spent Climbing	Climb 2 Total Time	Climb 2 Rest Time	Climb 2 Time Spent Climbing	Climb 3 Total Time	Climb 3 Rest Time	Climb 3 Time Spent Climbing
Mass (kg)	Pearson Correlation	,533*	0,450	0,436	,530*	,494*	0,431	,562*	,568*	0,387
	Sig. (2-tailed)	0,035	0,070	0,080	0,029	0,044	0,084	0,019	0,017	0,124
	N	17	17	17	17	17	17	17	17	17
Skinfolds (mm)	Pearson Correlation	0,476	,520*	0,247	,506*	,556*	0,270	,545*	,616*	0,242
	Sig. (2-tailed)	0,062	0,039	0,357	0,046	0,025	0,312	0,029	0,011	0,366
	N	16	16	16	16	16	16	16	16	16
VO_{2max} Chester Step Test	Pearson Correlation	–0,295	–,483*	0,059	–0,350	–,529*	0,025	–0,354	–,515*	0,028
	Sig. (2-tailed)	0,250	0,050	0,823	0,169	0,029	0,923	0,164	0,035	0,915
	N	17	17	17	17	17	17	17	17	17

* Correlation is significant at the 0,05 level (2-tailed)

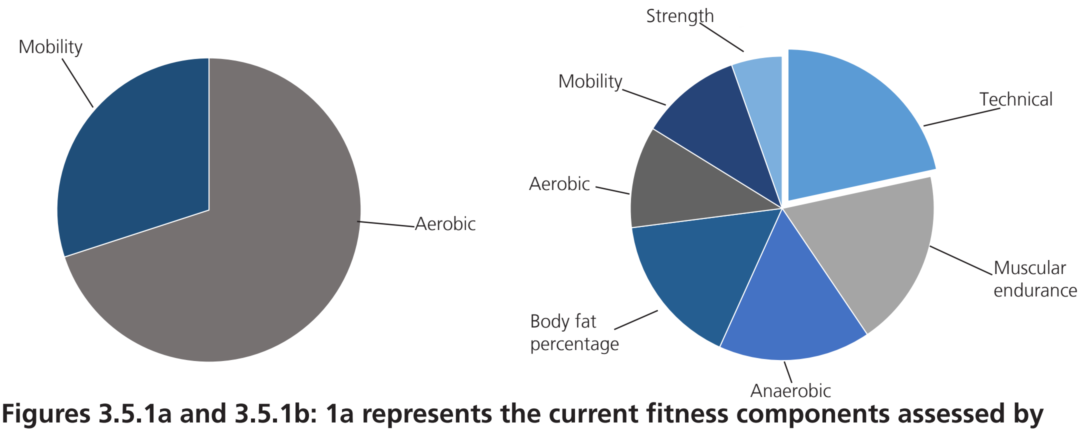
Participant Feedback

Each of the seven WT were asked how they felt the climbing task related to their job. Each WT felt that it was comparable to running outside and running on a treadmill. One participant found it easier/more comfortable compared to climbing the tower especially the external ladders. Another participant reported changing technique to accommodate the difference in rung dimension; they stated that when climbing a ladder on a wind turbine they would use a hook method with the hand as opposed to wrapping the thumb around the rung, which was the technique they adopted here. This participant felt this might have contributed to the fatigue felt in the arms. All of the taller WT stated that when climbing the tower they would lean against the wall, where possible, to remove some of the strain from their hands as they ascended; this was not an option in the present study or for shorter climbers.

Every participant stated they felt fatigue in the forearms, those that took breaks stating this was the reason for stopping, not leg fatigue or being out of breath. With most stating that they wanted to climb faster as it was more comfortable. The muscular fatigue led to delayed onset of muscle soreness felt 1 to 2 days after climbing in a number of participants. In some this lasted for up to 4 days (n = 3), others reported minimal fatigue the next day (n = 4). A number of participants (n = 6) reported blistering of the hands following the three climbs.

3.5 DISCUSSION

Experienced WT demonstrated faster climbing speeds, took less rest, had fewer self-selected rest breaks and ultimately took less time (Climb 1 = 3 min 13 s; *NB:* WT had the addition of a sea survival suit; Climb 2 = 4 min 25 s and Climb 3 = 5 min 14 s) to complete each of the three 120 m climbs than the novice climbers. With time increasing over the three climbs (*i.e.* time spent climbing and resting). It should be noted that a larger variation was observed within the novice climbers, with some performing to the same levels as the WT. These data suggest that whilst the WT were neither fitter nor stronger than the novice climbers, their experience meant they were better suited to dealing with the physical demand of the climbs (specific ladder climbing fitness). This study has shown that ladder climbing is a combination of multiple components of fitness (Figures 3.5.1a and 3.5.1b). However, when comparing WT to novices, it is clear that technique and experience improves performance, reduces the physiological burden and maintains optimal movement patterns for longer. Therefore, it is recommended that future work evaluates: what constitutes an experienced WT; what the minimum acceptable standards are to climb a ladder in the Wind Power Industry; how long it takes to become proficient at prolonged ladder climbing using the minimum acceptable standards, and if training can improve the time to proficiency.



Figures 3.5.1a and 3.5.1b: 1a represents the current fitness components assessed by the wind power industry. 1b shows all the fitness components identified during this study and their assessed relative contribution to ladder climbing performance

Unlike other studies (Energy Institute, 2010; Barron 2017), where the climbing speed was fixed at 24 rungs.min^{-1} and 34,5 rungs.min^{-1}, climbers in this study could self-select their ascending speed. WT and novice climbers chose to climb between 30 rungs.min^{-1} to 66,67 rungs.min^{-1}, with individuals reporting that the slower they climbed the more fatigue they felt in their arms. This suggest that minimum climbing speeds recommend for the Oil and Gas Industry (24 rungs.min^{-1} and 34,5 rungs.min^{-1}) are not suitable for use within Wind Power, and should not be used to set standards to assess physical fitness. Further work is required to determine a minimum acceptable climbing speed that minimising forearm fatigue.

Ascending a vertical ladder 120 m has a high physical demand as demonstrated by the percentage of time spent metabolising energy anaerobically to aerobically, when 2/3 of the total time taken to complete 120 m was rest. This is also supported by high peak HRs and $\dot{V}O_2$. It is unclear from these data whether smaller individuals would face an increased physical burden due to the kit being carried. It is likely that those (small or large) with high fat masses will struggle equally with climbing a vertical ladder. Initial correlation analysis suggests that individuals who are heavier with a higher sum of skinfolds (*i.e.* higher levels of body fat) will take longer to complete 120 m ladder climb and take longer rests during the climb, with a higher number of rest breaks needed. The $\dot{V}O_{2max}$ data, as predicted by the Chester step test suggested that individuals with lower aerobic capacity would require longer rests. Therefore, it is recommended that future research determine suitable fitness requirements for WT.

Even though participants were provided with time to familiarise with the manual dexterity task, improvements in performance were observed across each climb. However, no differences were observed when comparing times pre and post climbs. This suggests that the ladder climb effected individual's ability to perform a task with a fine motor control component. The rest received between each climb was then enough to allow performance to improve through continued familiarisation. It is suggested that this stagnation in performance pre and post was due to the reduction in grip strength and endurance. Further work is needed to quantify the magnitude of this effect once participants have been more fully familiarised with the task.

The data on muscle activity, grip strength and endurance supported the subjective feedback that the reason for resting during the ladder climb was due to fatigue in the forearms. This fatigue was noted to last several days in some participants, suggesting if large volumes of climbing were to take place on multiple days performance could be impaired and injury risk increased, especially in novice climbers of those that do not climb regularly.

The kinematic data shows that wearing a sea survival suit changes movement patterns such that WT are less efficient. Therefore, it is recommended that sea survival suits are only worn when transferring from the vessel to the TP, once inside the turbine they should be removed.

The toe marker distance is important to consider as it displays the proximity to the ladder as the climber fatigues. Toe clearance has been identified previously as an important variable in slip avoidance. A known threshold, whereby the climber is more likely to fall, does not exist. However, the significant decreases presented in this study between climb 1 and climbs 2 and 3 indicates that the climbers are increasing the risk of trips. Additionally the distance decreases after the first climb for both groups showing a single 120 m climb can make a wind turbine technician more susceptible to tripping. As participants became more fatigued, the distance between the toe and the ladder decreased. The standard deviations associated with the overall climbing data represent the changes that occur. As can be seen in Table 3.4.22, the standard deviations increase as the climbs continue. This indicates that the participants became more variable in foot movement patterns as the climbs continued. No significant differences were found between the ascent data and the descent data. Based upon the literature, it was expected that the descent data would show a smaller distance. It is accepted that the task during the descent did not replicate the true descent carried out by a wind turbine technician. Further research, focussing on a longer descent may provide greater insight.

Novice climbers demonstrated less range of movement through the hips and a higher proportion of muscle activation in the upper body than the WT. This means they were using less of the large muscle groups of the legs and more of the small muscles in the arms. The reliance on the forearm increased as the climbs continued and a potential cause for concern. The use of smaller muscles in the arm led to fatigue as early as the second climb. Almost all participants, irrespective of climbing experience, reported that the forearms were a limiting factor in the climbing performance. The WT did not increase the use of the forearm from the first to the second climb. However, this increased significantly in the final climb. The novices increased from the first to the second and again to the final climb. This would indicate that the familiarity with climbing allowed the limit the use of this smaller muscle until the final climb. Anecdotally, it was observed that some novices changed their technique dramatically in the final climb (using the wrists to support the upright position and climbing with the legs), allowing them to continue climbing when the grip had reduced. This may have led to large standard deviations in the data with the forearm registering higher values if the same technique had continued. From a practical perspective, the significant increase from Climb 1 to Climb 2 informs us that perhaps consideration should be taken when climbing 120 metres more than once in a day, ultimately, leading to greater fatigue and increase the likelihood of injuries through loss of grip. The increased shoulder flexion angles of both groups after the first climb demonstrates that one climb is sufficient to increase the amount of reaching for the rungs of the ladder. This reaching action has been shown to lead to chronic shoulder injury.

3.6 SUMMARY

- Experienced WT demonstrated faster climbing speeds, took less rest, had fewer rest breaks and ultimately took less time to climb each of the three 120 m than the novice climbers. With the magnitude of difference increasing over the three climbs with respect to total time (*i.e.* time spent climbing and resting).
- The minimum climbing speeds recommend for the Oil and Gas Industry (24 rungs.min^{-1} and 34,5 rungs.min^{-1}) are not suitable for use within Wind Power and should not be used to set standards to assess physical fitness.
- It is suggested that the ladder climb impaired the ability to perform a task with a fine motor control component.
- Ladder climbing is a combination of multiple components of fitness (Figures 3.4.1a and 3.4.1b). However, when comparing WT to novices it is clear that technique and experience improve performance, reduce the physiological burden and maintain optimal movement patterns for longer. Therefore, to optimise the well-being and reduce the risk of injuries new WT, and those that climb infrequently, would benefit from a training package that optimises climbing technique.
- Wearing a sea survival suit changes movement patterns such that WT are less efficient. Therefore, it is recommended that they are only worn when transferring from the vessel to the TP, once inside the turbine they should be removed.
- Due to increased levels of fatigue associated with multiple climbs, toe clearance was reduced. This has been shown in the literature to increase the likelihood of trips and potential for injury.

- Changes were observed in the shoulder joint which suggested that as fatigue increased, due to multiple climbs, participants were changing their technique to reach higher with their arms. It has been shown in the literature (non-ladder climbing specific) that this repetitive movement in shoulder movement leads to an increased risk of chronic shoulder injuries.
- Novices demonstrated less range of movement through the hips and a higher proportion of muscle activation in the upper body than the WT. This means they were using less of the large muscle groups of the legs and more of the small muscles in the arms. Ultimately, this will lead to an earlier onset of fatigue and increase the likelihood of injuries through loss of grip.
- The data on muscle activity, grip strength and endurance support the subjective feedback that the reason for resting during the ladder climb was due to fatigue in the forearms. This fatigue was noted to last multiple days in some participants suggesting if large volumes of climbing were to take place on multiple days performance could be effected and injury risk increased, especially in novice climbers of those that do not climb regularly.

3.7 RECOMMENDATIONS AND FUTURE RESEARCH

Therefore, it is recommended that future work evaluates:

- What constitutes an experienced WT?
- What the minimum acceptable standards are to climb a ladder in the Wind Power Industry?
- How long it takes to become proficient at prolonged ladder climbing using the minimum acceptable standards?
- Does training improve the time to proficiency?
- The effect of multiple days climbing and an accumulation of fatigue and recovery should be investigated to determine the impact on job performance, physical fitness requirement and injury.
- Consideration should be given to the gloves issued to WT to minimise the risk of this short term injury.

4 THERMAL ASPECTS

4.1 OBJECTIVES

To investigate the effects of heat stress on the technician whilst climbing and their ability to perform their work safely after multiple ladder climbs.

4.2 BACKGROUND

There is an important distinction to be made between 'external' and 'internal' heat load. 'External' comes from a hot environment, 'internal' from the body as a result of exercise. For example, internal heat load would arise from the exercise required to transfer to, and climb, ladders in the towers of wind turbines. Thus, someone exercising hard in a Survival Suit could become dangerously hyperthermic in even a relatively cool environment. A limit on the intensity and or duration of exercise can be estimated if work intensity, duration and body mass are known and it is assumed that only a small percentage of the heat produced by exercise is lost to the environment. Using such a calculation, dangerous levels of hyperthermia are unlikely to occur with less than 10–20 minutes of continuous moderate exercise.

An individual at rest in a hot environment, such as the cabin of a transfer vessel, may become uncomfortably warm but is unlikely to have dangerous increases in deep body temperature (hyperthermia) even when wearing a Survival Suit. However, they may become dehydrated over time if fluid and a rehydration policy are not in place.

Dehydration during exercise in the heat
During exercise, body fluid loss, primarily due to sweating, increases by an amount that depends on several factors including environmental temperature, fitness, level of acclimatisation, intensity and duration of the activity. Without adequate fluid replacement, body fluid levels will fall and dehydration occur. In comparison with the responses seen when hydrated, fluid loss equivalent to 1 % to 5 % of body mass increases deep body temperature due to decreased sweating and cutaneous blood flow. Dehydration between 1,9 % and 4,3 % of body mass can reduce physical endurance time by 22 % to 48 %.

The risks of light-headedness, fatigue and heat illness are increased if exercise is undertaken in the heat in a dehydrated state. Hydration status can be monitored using a variety of techniques. In the work-place the most straightforward approaches for ensuring people maintain hydration levels are to have fluid freely available, encourage people to drink a little more than they need to quench their thirst and to keep an eye on the colour of their urine (urine colour charts).

Heat Illnesses
The consequences of an inability to control deep body temperature is heat illness. This includes:

a. *Heat-related light-headedness/syncope (fainting)/hypotension (low blood pressure):* this is the most likely form of heat illness for those experiencing passive heating, such as might occur in people at rest in warm environments in the cabin of a transfer boat. It increases the likelihood of people feeling light-headed on assuming an upright posture. The longer an individual remains in the heat, the more dehydrated they become, the more clothing (including protective clothing) they are wearing, the more likely they are to experience this form of heat illness.

b. *The 'physiological cost' associated with vasodilatation and sweating:* maximum vasodilatation increases skin blood flow to as much a 3 $L.min^{-1}$. Maximum sweat rates of up to 2 $L.hr^{-1}$ can occur in humans resulting in dehydration. The combination of dehydration and vasodilatation can put a significant strain on the cardiovascular system and a mismatch between peripheral vasodilatation and increased cardiac output can compromise mean arterial blood pressure. This fall in mean arterial blood pressure can occur by the time deep body temperature has risen by 0,5 °C (Fan *et al.* 2008). Dehydration and decreased blood pressure reduce skin blood flow which can impair skin circulation and sweating, resulting in higher skin temperatures.

c. *Heat Cramps:* usually occur in the specific muscles exercised due to an imbalance in the body's fluid volume and electrolyte concentration, and low energy stores. Can be prevented by an appropriate rehydration strategy and treated by stretching and massage.

d. *Heat Exhaustion:* the most common form of heat illness, defined as the inability to continue exercise in the heat. Usually seen in unacclimatised individuals. Caused by ineffective circulatory adjustments and reduced blood volume. Characterised by breathlessness, hyperventilation, weak and rapid pulse, low blood pressure, dizziness, headache, flushed skin, nausea, paradoxical chills, irritability, lethargy and general weakness.

e. *Heat Stroke:* medical emergency resulting from failure of the thermoregulatory system as a result of a high deep body temperature (>40,5 °C). Characterised by confusion, absence of sweating, hot and dry skin, circulatory instability. If not treated by immediate cooling, results in death from circulatory collapse and multi organ damage.

4.3 METHODS

Please refer to section 3.3 for a detailed account of the methods. It should be noted that the measurement of energy expenditure during each climb (calculated from oxygen consumption) was the average of the climb and rest phase for each ladder climb. This allowed the calculation of total heat production due to each climb.

As discussed in the tender document for this project, the time available limited the thermal assessment that could be undertaken and, therefore, only a general insight into the responses observed with ladder climbing can be provided at this time; both the conditions tested and the range and number of participants tested limit the utility of the data. However, there are some patterns that emerge, and a demonstration of what can be done with the data is presented. If thought useful, the project could be followed up and expanded to remove some of the constraints (e.g. in terms of conditions tested, numbers tested).

4.4 RESULTS

The physical characteristics of the participants for this assessment are presented in Table 4.4.1.

Table 4.4.1: Physical characteristics of the participants taking part in the thermal assessment (n = 7; Males = 5; Female = 2)

Participant/Sex (M = male; F = female)	Age (y)	Height (cm)	Weight (kg)	Chester Step Test (mL.kg^{-1}.min^{-1})
1/F	32	174,2	59	61
2/M	50	178,9	80,5	60
3/F	32	167,5	65	50
4/M	36	185,6	100	48
5/M	37	184,9	95	48
6/M	35	183,9	72,5	47
7/M	49	172,1	76,5	43

The mean (SD) conditions during the testing were: ambient temperature (Ta) 19,3 (2,3) °C; relative humidity 43,6 (10,2) %.

Mechanical efficiency (ME) is the effectiveness of a machine or body in transforming the energy and power that is input to the device (metabolism in humans) into an output force and movement (work done = force [mass] × distance [climbed]). The mean (SD) mechanical efficiency during the climbs with the survival suit was 14,6 (3,4) %. The corresponding figures for the overalls was 16,3 (5,12) %. These figures compare with a mechanical efficiency of walking, for example, of 35 % to 40 % (Cavagna, and Kaneko,1977). It should be noted that the figures obtained for ME in the present tests unavoidably included work and rest periods. However, they still provide some insight into what was happening. Although, as might be expected, the numeric ME figure for ladder climbing whilst wearing a survival suit is lower than that when wearing just overalls, no statistical comparison was done due to low participant numbers: more volunteers are likely to be needed to identify a significant difference in this finding. It is worth noting that by far the best ladder climber of the cohort of participants achieved a mechanical efficiency that was approximately 5 % (by these calculations) better than the other participants. This is also reflected in a relatively slow rate of rise of deep body temperature (Tpill, Figure 4.4.1, Participant 1).

The ME of an activity can be used, along with metabolic rate (from oxygen consumption) to calculate the heat production for an activity. Table 4.4.2 demonstrates the thermal responses based on the data collected during the experiments, with a theoretical assessment (final column) of how deep body temperature would have changed if all the heat generated by climbing the ladder had contributed to raising deep body temperature and none had been transferred to the environment. Note, this is a worst case scenario and will not happen (some heat should always be transferred under normal circumstances) but gives an idea of the most extreme responses in the conditions of the tests.

Table 4.4.2: Thermal data collected during each ladder climb of 120 m for each participant who completed the condition. SS = survival suit condition; O = overall condition; s = start; f = end of stepping; na = missing data

Participant	Condition	Tpill s (°C)	Tpill f (°C)	Δ T pill (°C)	Change in heat content (kJ)*	Heat production (kJ/s)	Predicted Tpill at end if no heat lost (°C)**
1	1 SS	37,26	37,59	0,33	67,8	0,370	38,85
	2 O	36,90	37,03	0,13	26,7	0,306	38,04
	3 O	37,32	37,43	0,11	22,6	0,324	38,50
2	1 SS	37,24	38,32	1,08	302,6	0,579	39,35
	2 O	37,08	37,71	0,63	176,5	0,559	39,32
	3 O	37,16	37,83	0,67	187,7	0,572	39,70
3	1 SS	37,45	38,26	0,81	183,2	0,367	39,91
	2 O	37,51	38,09	0,58	131,2	0,394	40,25
	3 O	37,74	38,13	0,39	88,2	na	na
4	1 SS	37,26	38,22	0,96	334,1	0,612	40,40
	2 O	37,42	38,24	0,82	285,4	0,524	39,22
	3 O	37,50	38,56	1,06	368,9	na	na
5	1 SS	37,09	37,84	0,75	248,0	0,546	39,23
	2 O	37,46	37,98	0,52	171,9	0,537	39,47
	3 O	37,36	37,85	0,49	162,0	0,534	39,46
6	1 SS	37,18	37,80	0,62	156,4	0,427	40,22
	2 O	36,93	37,41	0,48	121,1	0,498	39,73
	3 O	37,10	37,52	0,42	106,0	0,484	39,98
7	1 SS	37,08	37,35	0,27	71,9	0,391	39,17

* Heat content based only on pill (deep body) temperature, not on mean body temperature as skin temperatures were measured in these studies.
** Prediction based on heat production figures for each participant and condition and assuming no heat loss *i.e.* the worst case scenario.

In the mean data presented below, the data for participant 7 have been excluded as they only undertook the first condition, before stopping due to dizziness, pins and needles in the arms and a tight chest.

The mean (SD) time spent climbing in the survival suit was 23 min 4 s. The mean (SD) time spent climbing in the overalls was 20 min 11 s. From the data collected during Climb 1, the measured mean (SD) change in deep body temperature (Tpill) in the survival suit was: 0,76 (0,26) °C (n = 6). From the data collected during Climbs 2 and 3, the measured mean (SD) change in Tpill in the overalls was: 0,485 (0,22) °C (n = 10). From these data, the mean rate of increase in Tpill when wearing a survival suit was 0,033 $°C.min^{-1}$. The corresponding mean rate of increase in Tpill when wearing overalls was 0,024 $°C.min^{-1}$. The worst case scenario (no heat loss), calculated from the heat production data collected, gives a mean (SD) change in Tpill in the survival suit during climbing/resting as: 2,41 (0,59) °C (n = 6). The worst case scenario (no heat loss), calculated from the heat production data collected, gives a mean (SD) change in Tpill in the overalls during stepping as: 2,14 (0,63) °C (n = 6). From these data, and using the total time spent climbing/resting, the mean rate of increase in Tpill when wearing a survival suit was 0,105 °C.min^{-1}. The corresponding mean rate of increase in Tpill when wearing overalls was 0,106 °C.min^{-1}.

As a rough guide, and assuming a linear rate of increase in deep body temperature from the start of ladder climbing (Figure 4.4.1), the rates above can be used to calculate a time to a given deep body temperature when climbing and resting volitionally, as in the present study. The final deep body temperature to use varies, the military use 38,5 °C (Santee, and Wallace, 2005). Using this figure, the times to reach a deep body temperature of 38,5 °C can be calculated assuming a starting temperature of 37 °C (Table 4.2.3). The same data can be calculated from the actual graphical Tpill data collected from each of the participants (Figures 4.4.1a–g) by simple extrapolation.

Table 4.4.3: Estimated time to reach a deep body temperature of 38,5 °C. Calculated on the basis of direct measurements in the present study, as well as calculated theoretical maximum changes (worst case, no heat loss) from heat production data

Condition	Time to 38,5 °C (min)
Survival Suit using Tpill data from current study	45,5
Overalls using Tpill data from current study	62,5
Survival Suit using calculated worst case scenario	14,3
Overalls using calculated worst case scenario	14,2

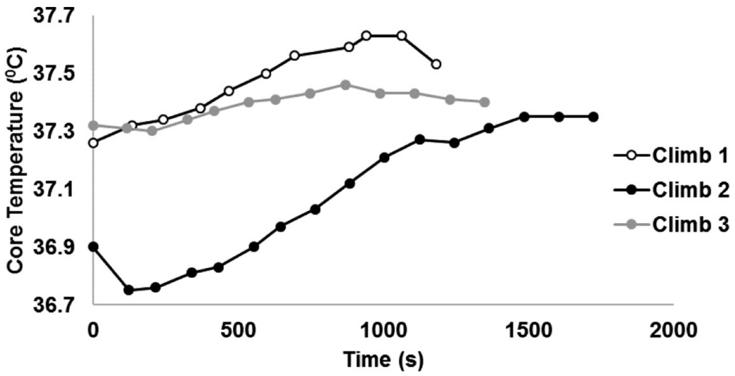


Figure 4.4.1a: Participant 1

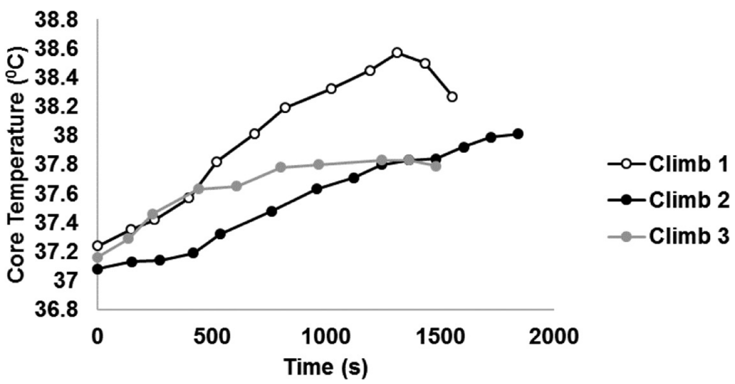


Figure 4.4.1b: Participant 2

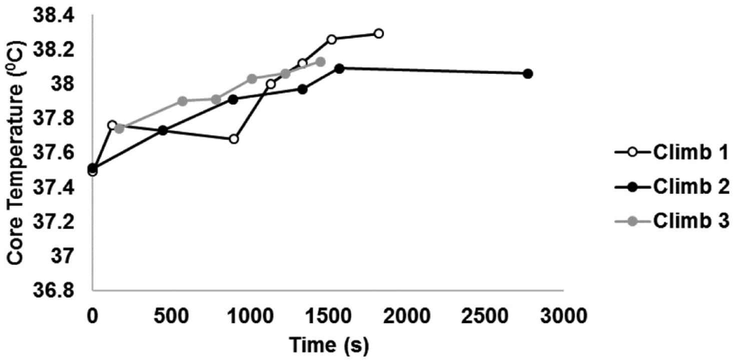


Figure 4.4.1c: Participant 3

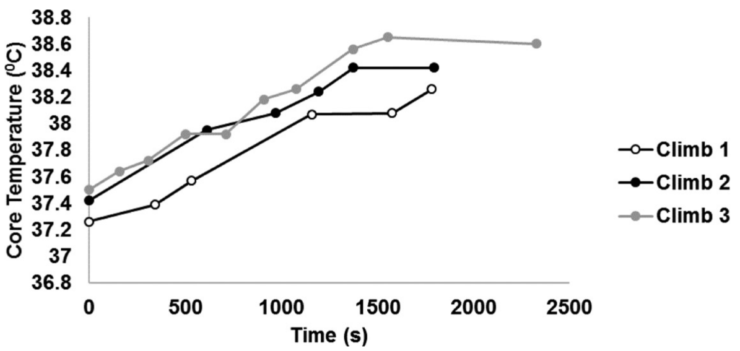


Figure 4.4.1d: Participant 4

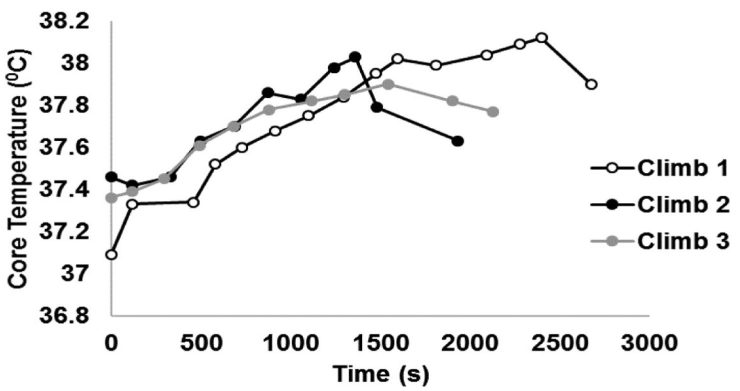


Figure 4.4.1e: Participant 5

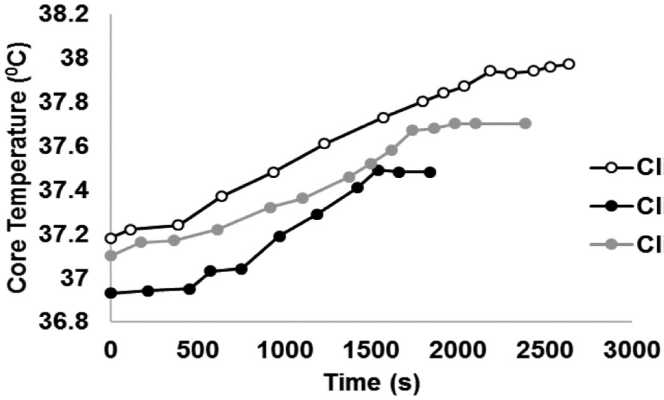


Figure 4.4.1f: Participant 6

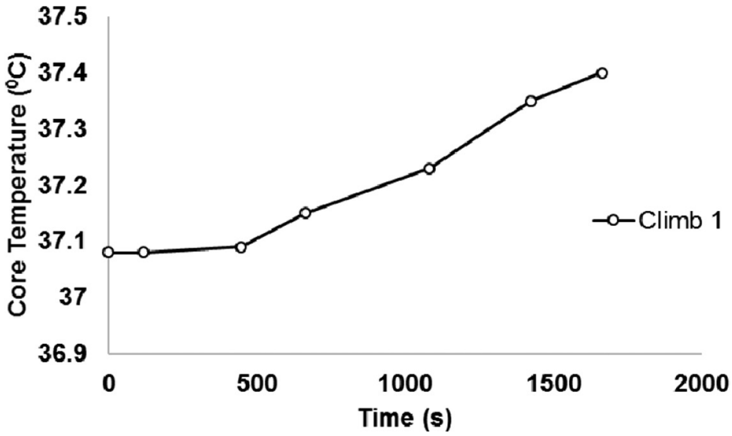


Figure 4.4.1g: Participant 7

Figure 4.4.1: Deep body temperature (Tpill) data for all of the participants in each condition. Climb 1 with the addition of a sea survival suit (n = 7; males = 5; females = 2)

4.5 DISCUSSION

Due to time limitations and size of the project, this thermal study was no more than a simple pilot study to obtain an idea of the thermal responses of people climbing a ladder in an indoor environment. If the results are considered to be of value, a more comprehensive study incorporating more environments (temperatures, humilities, radiant heat loads), people (larger sample) and fieldwork (measurement during a working day) could be worked-up.

The survival suit condition represented the greatest thermal burden with 8 % less of the heat being produced being lost to the environment in this condition compared to when overalls were being worn. However, the participants in this study were able to set their own work/rest schedule whilst climbing 120 m on three separate occasions. It also appears that they dealt with the additional demands of the survival suit condition by resting more during the climbs in this condition: on average, the participants took nearly 3 minutes longer to climb 120 m when wearing a survival suit compared to overalls.

It seems likely that the decision to rest (stop climbing) was primarily based on arm fatigue; however, thermal discomfort may have contributed to this decision. Because the survival suit condition represented a greater absolute load as well as thermal load than the overalls condition (total mass 91,1 kg vs. 88,4 kg), it is not possible to separate the thermal determinants of the decision to stop climbing from those caused by fatigue: harder work leads to earlier fatigue and higher body temperatures. There is a theory that a 'critical' core temperature exists that, when attained, results in a reduced central drive to exercise (Nybo and Neilsen, 2001*)*. However, this temperature is thought to be around 40 °C, higher than that seen in the present study. It is possible that this deep critical deep body temperature is lower if skin temperatures are high (as likely in the present tests).

The performance of exercise increases deep body temperature in almost all circumstance. Therefore, it is to be expected that ladder climbing would increase deep body temperature, however, the deep body temperatures reached during any one of the 120 m climbs are not a cause for concern from a hyperthermic perspective (Table 4.4.2). This may change if several climbs are undertaken in a day and the later climbs are commenced with a raised deep body temperature. The figures provided, in terms of rates of change of deep body temperature (survival suit 0,033 $°C.min^{-1}$; overalls 0,024 $°C.min^{-1}$), can be easily used to re-calculate how long it will take the deep body temperature of an individual to get to 38,5 °C if they start with a temperature higher than 37 °C. The theoretical maximum deep body temperatures (Table 4.4.2) are more concerning, but represent a circumstance that will rarely occur (zero heat loss to the environment).

A more likely heat-related problem to be encountered by WT is the impact of raised deep body temperature on cardiovascular and blood pressure control. This problem will be compounded by dehydration (see Background: 'Heat-related light-headedness/syncope [fainting]/ hypotension [low blood pressure]' and 'Heat Exhaustion'). The combination of increasing body temperatures, increased skin blood flow and hard work can result in discomfort, stress (hyperventilation and consequent peripheral tingling) and light-headedness. These, and the early symptoms of heat exhaustion (see Background), were reported by Participant 7 who had to withdraw from the present study.

It is concluded that, when left to their own devices, WT are likely to settle upon a work/rest schedule that means they can climb 120 m without a direct risk from hyperthermia. More concerning is the impact of heating on discomfort, cardiovascular control and the maintenance of blood pressure. This may lead individuals, particularly if dehydrated, to feel light-headed.

4.6 RECOMMENDATIONS

A more thorough, including field-based measurements, assessment of the thermal responses of WT to a representative range of environmental conditions should be undertaken.

From the thermal perspective, those with responsibility for the well-being of WT should ensure that the technicians have the opportunity to cool down and rehydrate following prolonged ladder climbs e.g. 30 m to 120 m. High aerobic fitness and technical ladder climbing skills should be encouraged/taught – these have a directly beneficial impact on the stress associated with ladder climbing.

REFERENCES

Allsopp, A.J. Scarpello, E.G. Andrews S. and Pethybridge R.J. (2003). Survival of the Fittest? The Scientific Basis of the Royal Navy Pre-Joining Fitness Test. *Journal of Royal Naval Medical Service, 89*(1), 11–18

Anderson, J.A.D. (1981). Low back pain – cause and prevention of long term handicap (a critical review). *Injury Rehabilitation and Medicine, 3*, 89–93

Anderson, G.S. Plecas, D.L. and Segger, T. (2001). Police Officer physical ability testing: Re-validating a selection criteria. *International Journal of Police Strategies and Management*, *24*(1): 8–31

Arlinghaus A., Lombardi D.A., Courtney T.K., Christiani D.C., Folkard S., Perry M.J. (2012) The effect of rest breaks on time to injury – a study on work-related ladder-fall injuries in the United States *Scandinavian Journal of Work and Environmental Health*. (2012) 38(6) 560–567

Armstrong T.J., Young J., Woolley C., Ashton-Miller J. and Kim H. (2009). 'Biomechanical Aspects of Fixed Ladder Climbing: Style, Ladder Tilt and Carrying.' *Proceedings of the Human Factors and Ergonomics Society 53rd Annual Meeting*, San Antonio. 935–939

Ayoub, M.M., and Bakken, G.M. (1978). An ergonomic analysis of selected sections in subpart D, walking and working surfaces. Service Contract No. B-9-F-8-1320, Institute for Biotechnology, Texas Tech University TX

Barnett, R., and P. Poczynck. 2000. 'Ladder Rung vs. Siderail Hand Grip Strategies.' Safety Brief (Triodyne Inc.) 16 (4): 1–15

Barron, P.J., Burgess, K., Cooper, K., and Stewart, A.D. (2017). The physiological effect of a 'climb assist' device on vertical ladder climbing. *Ergonomics*, *60* (7), 1008–1013

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), 172–176

Biddle, D. and Shepherd-Sill, N. (1999). Protective Service physical ability Tests: Establishing Pass/Fail Cut-offs for Physical Ability Tests. *Public Personnel Management, 28*(2), 217–224

Bloswick D.S., Chaffin D.B. (1990) An ergonomic analysis of the ladder climbing activity. *International Journal of Industrial Ergonomics*. 6: 17–27

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

Borg, G. Hassmén, P. and Lagerström, M. (1987). Perceived exertion related to heart rate and blood lactate during arm and leg exercise. *European Journal of Applied Physiology and Occupational Physiology; 56*(6) 679–685

Buckley, J.P. Sim, J. Eston, R.G. Hession, R. and Fox, R. (2004). Reliability and validity of measures taken during the Chester step test to predict aerobic power and prescribe aerobic exercise. *British Journal of Sports Medicine, 38,* 197–205

Cavagna, G.A., and Kaneko, M. (1977). Mechanical work and efficiency in level walking and running. *The Journal of Physiology, 268*(2), 467–481

Chahal, P. Lee, S.W. Oseen, M. Singh, M. and Wheeler, G. (1992). Physical fitness and work performance standards: A proposed approach. *International Journal of Industrial Ergonomics, 9*, 127–135

Cohen, J. (1988). Statistical power analysis for the behavioural sciences, 2nd Ed. Hillside New Jersey: Lawrence Erlbaum Associates

Cornelius, K.M., Redfern, M.S., and Steiner, L.J. (1994) 'Postural stability after whole-body vibration exposure.' *International Journal of Industrial Ergonomics* 13 (4):343–351

Davis, P.O. and Dotson, C.O. (1987). Job performance Testing: an alternative to age discrimination. *Medicine and Science in Sports and Exercise, 19*(2), 179–185

Douris, P., McKenna, R., Madigan, K., Cesarski, B., Costiera, R., and Lu, M. (2003). Recovery of maximal isometric grip strength following cold immersion. *Journal of Strength and Conditioning Research, 17*(3), 509–513

Durnin, J.V.G.A. and Womersley, J. (1974). Body fat assessed from total body density and its estimation from skinfold thickness: measurements on 481 men and women aged from 16 to 72 years. *British Journal of Nutrition 32*, 77–97

Energy Institute (2010). A Recommended Fitness Standard for the Oil and Gas Industry. ISBN 978 0 85293 562 0

Fan, J. L., Cotter, J. D., Lucas, R. A., Thomas, K., Wilson, L., and Ainslie, P. N. (2008). Human cardiorespiratory and cerebrovascular function during severe passive hyperthermia: effects of mild hypohydration. *Journal of Applied Physiology, 105*(2), 433–445

G9 Offshore Wind Health and Safety Association. In partnership with the Energy Institute (2014). Good practice guideline working at height in the offshore wind industry. ISBN 978 0 85293 720 4

Gallagher S, Hamrick C.A, Cornelius KM, Redfern MS. (2001) The effects of restricted workspace on lumbar spine loading. *Occupational Ergonomics*; 201–213

Gledhill, N., and Jamnik, V.K. (1992). Characterization of the physical demands of firefighting. *Canadian Journal of Sport Sciences = Journal Canadien des Sciences du Sport, 17*(3) 207–213

Greenberg, G.J. and Berger, R.A. (1983). A Model to Assess One's Ability to Apprehend and restrain a Resisting Suspect in Police Work. *Journal of Occupational Medicine, 25*(11) 809–813

Gumieniak, R. Jamnik, V.K. and Gledhill, N. (2011). Physical Fitness Bona Fide Occupational Requirements for Safety-Related Physically Demanding Occupations; Development Considerations. *Health and Fitness Journal Canada, 4*(2), 47–52

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

Health and Safety Executive (2014). Safe use of ladders and stepladders: A brief guide. ISBN: 9780717665181

Hodgdon, J.A. and Jackson, A.S. (2000). Physical test validation for job selection In: Constable, S. and Palmer, B. (Eds.) *The Process of Physical Fitness Standards Development* (pp.139–177). U.S. Human Systems IAC SOAR

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

Kamon E. (1970) Negative and Positive work in Climbing a Laddermill. *Journal of Applied Physiology* 29 (1) 1–5

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

Karvonen, M.J. Kentala, E. and Mustala, O. (1957). The effects of training on heart rate; a longitudinal study. In *Annales medicinae experimentalis et biologiae Fenniae, 35*(3), 307

Klien, B.W. (1986). Missed Work and Lost Hours Monthly. *Monthly Laboratory Review*, *109*, 26–30

Leyk, D., Rode, U., Erley, O., Gorges, W., Wunderlich, M., Rther, T., and Essfeld, D. (2006). Recovery of hand grip strength and hand steadiness after exhausting manual stretcher carriage. *European Journal of Applied Physiology*, 96, 593–599

Lipscomb, H.J. Schoenfisch A.L. Shishlov K.S. Myers, D.J. (2010) Nonfatal tool – or Equipment Related Injuries treated in US Emergency departments Among Workers in the Construction Industry, 1998–2005. *American Journal of Industrial Medicine* 53; 581–587

Marigold, D.S., Eng, J.J., Dawson, A.S., Inglis, J.T., Harris, J.E., Gylfadottir, S., (2005). Exercise leads to faster postural reflexes, improved balance and mobility, and fewer falls in older persons with chronic stroke. *Journal of the American Geriatric Society*. 53 (3) 416–423

McIntyre, D. R. (1983). Gait patterns during free choice ladder ascents. *Human Movement Science*, 2(3), 187–195

Milligan (2013). Fitness Standards for the Maritime and Coastguard Agency and the Oil and Gas Industry. PhD thesis

Milligan, G.S. Reilly, T.J. Zumbo, B. D. and Tipton, M.J. (2016). Validity and reliability of physical employment standards. *Applied Physiology, Nutrition, and Metabolism, 41*(6), S83–S91

Moore, SM, WL Porter, and PG Dempsey. 2009. 'Fall from equipment injuries in US mining: Identification of specific research areas for future investigation.' *Journal of Safety Research* 40 (6):455–460

Muir, l.L. and Kanwar, S. (1993) Ladder injuries *Injury* 24 (7) 485–487

Morken T., Mehlum I.S., Moen B.E. (2007) Work-related musculoskeletal disorders in Norway's offshore petroleum industry. *Occupational Medicine*. 57:112–117

Nuwayhid I.A. Stewart W, Johnson JV. Work activities and the onset of first time low back pain among New York City Fire-Fighters. (1993) *American Journal of Epidemiology. 137*(5) 539–548

Nybo, L., and Nielsen, B. (2001). Hyperthermia and central fatigue during prolonged exercise in humans. *Journal of Applied Physiology, 91*(3), 1055–1060

Oil and Gas UK (2008). Medical aspects of Fitness for Work Offshore: Guidance for Examining Physicians. ISBN: 9780717665181

Paul, A.J., Lovell, M., Campbell-Kyureghyan, N., and Beschorner, K. (2013). Biomechanical Response to Ladder Slipping Events: Effects of Hand Placement on Response and Recovery. *In American Society of Biomechanics Omaha*, Nebraska

Partridge, R.A., Virk, A.S., and Antosia, R.E. (1998). 'Causes and patterns of injury from ladder falls.' *Academic Emergency Medicine* 5 (1):31–34

Pelham TW, Rowe PRT, Robinson MG, Holt LE (2006) A research pilot project to test the efficacy of current pedorthic practices in the Canadian forces *Work 26,* (2) 207–214

Pliner E., Beschorner, K.T. (2017) Effects of Ladder Climbing Patterns on Fall Severity *Proceedings of the Human Factors and Ergonomics Society 2017 Annual Meeting* Volume: 61 (1) 940–944

Pliner, E.M., Campbell-Kyureghyan, N. H., and Beschorner, K.E. (2014). Effects of foot placement, hand positioning, age and climbing biodynamics on ladder slip outcomes. *Ergonomics*, 57(11), 1739–1749

Pliner, E.M., Seo, N.J., and Beschorner, K.E. (2015). Hand and foot responses that improve ladder fall recovery. *Paper presented at the American Society of Biomechanics*, Columbus, OH

Pliner, E. M., Seo, N. J., and Beschorner, K. E. (2017). Factors affecting fall severity from a ladder: Impact of climbing direction, gloves, gender and adaptation. *Applied Ergonomics*, 60, 163–170

Rayson, M.P. and Holliman, D. (1995). Physical Selection Procedures for the British Army. Phase 4: Predictors of task performance in trained soldiers. DRA/CHS/PHYS/CR95/017, 1–45

Rayson, M.P. Holliman, D. and Belyavin, A. (2000a). Development of physical selection procedures for the British army. Phase 2. Relationship between physical tests and criterion tasks. *Ergonomics, 43*(1). 73–105

Rayson, M.P. (2000b). Fitness for work: the need for conducting a job analysis. *Journal of Occupational Medicine, 50*(6), 434–436

Reilly, T. Wooler, A. and Tipton, M. (2006a). Occupational Fitness Standards for Beach Lifeguards Phase 1: the physiological demands of Beach Lifeguarding. *Occupational Medicine, 56*, 6–11

Reilly, T., Iggleden, C., Gennser, M., and Tipton, M. (2006b). Occupational Fitness Standards for Beach Lifeguards phase 2: the development of an easily administered fitness test. *Occupational Medicine*, *56*, 12–17

Reilly, T. (2007). Fitness Standards for the Royal National Life Boat Institution (RNLI) Lifeboat Crew. Ph.D

RenewableUK (2013). Medical Fitnss to Work – Wind turbines: Guidelines for near offshore and land based projects. Industry report

Rodgers, S.H. (1988). Job evaluation in worker fitness determination. *Journal of Occupational Medicine, 3*(2), 219–239

Santee, W.R., and Wallace, R.F. (2005). Comparison of weather service heat indices using a thermal model. *Journal of Thermal Biology, 30*(1), 65–72

Santos, B.R., Lariviere, C., Delisle, A., Plamondon, A., Boileau, P-E, and Imbeau, D. 2008. 'A laboratory study to quantify the biomechanical responses to whole-body vibration: The influence on balance, reflex response, muscular activity and fatigue.' *International Journal of Industrial Ergonomics*. 38:(7–8) 626–639

Schnorenberg, A.J., Campbell-Kyureghyan, N.H., and Beschorner, K.E. (2015). Biomechanical response to ladder slipping events: Effects of hand placement. *Journal of Biomechanics*, 48(14), 3810–3815

Shephard, R.J. and Bonneau, J. (2002). Assuring Gender Equity in recruitment Standards for Police Officers. *Canadian Journal of Sports Science, 27*(3). 263–295

Shepherd, G.W., Kahler, R.J., and Cross, J. (2006). 'Ergonomic design interventions–a case study involving portable ladders.' *Ergonomics* 49 (3) 221–234

Siddall, A.G., Standage, M., Stokes, K.A., and Bilzon, J.L.J. (2014). Development of occupational fitness standards for the UK Fire and Rescue Services (FRS). Department for Health, University of Bath, Bath, UK

Smith, G.S., Timmons, R.A., Lombardi, D.A., Mamidi, D.K., Matz, S., Courtney, T.K., Perry. M.J. (2006). 'Workrelated ladder fall fractures: identification and diagnosis validation using narrative text.' *Accident Analysis and Prevention* 38 (5):973–980

Stevenson, J.M.J. Bryant, T. Andrew, G.M. Smith, J.T., French, S.L. Thomson, J.M. and Deakin, J.M. (1992). Development of Physical Fitness Standards for Canadian Armed Forces, Younger Personnel. *Canadian Journal of Sport Science, 17*(3). 214–221

Sykes, K. and Roberts, A. (2004), The Chester step test – a simple yet effective tool for the prediction of aerobic capacity. *Physiotherapy, 90,* 183–188

Taylor, N.A.S. Groeller, H. (2003). Work-based Physiological Assessment of Physically-demanding Trades: a Methodological Overview. *Journal Physiology and Anthropology, 22,* 73–81

Tipton, M.J. Milligan, G.S., and Reilly, T.J. (2013). Physiological employment standards I. Occupational fitness standards: objectively subjective? *European Journal of Applied Physiology,* 113(10), 2435–2446

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

Whaley. M.H., Kaminsky, L.A., Dwyer, G.B., Getchell, L.H., and Norton J.A. (1992). Predictors of over- and underachievement of age-predicted maximal heart rate. *Medicine and Science in Sports and Exercise, 24*(10), 1173–1179

Young, Justin G., Charles Woolley, Thomas J. Armstrong, and James A. Ashton-Miller. (2009). 'Hand-Handhold Coupling: Effect of Handle Shape, Orientation, and Friction on Breakaway Strength.' Human Factors: *The Journal of the Human Factors and Ergonomics Society* 51 (5): 705–717

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