The demands of vertical ladder ergometer climbing relating to the wind energy industry.

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A thesis submitted in partial fulfilment of the requirement of the Robert Gordon University for the degree of Doctor of Philosophy

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Abstract

Peter James Barron

This thesis is submitted in partial fulfilment for the degree of Doctor of Philosophy.

The physiological and psychophysical demands of vertical ladder ergometer climbing relating to the wind energy industry.

The current medical fitness standard guidelines for Renewable UK for wind turbine technicians were adopted from the UK Fire and Rescue service. However, the two industries on the face of it have different demands. This thesis aimed to ascertain the day to day nature of the role of a wind turbine technician. Specifically, it aimed to understand the effect of external loads on vertical ladder ergometer climbing, the effect of a climb assist device and the effect space restriction on ladder climbing. A further aim was to understand the difference between climbing a pitched and vertical ladder ergometer.

Using an online survey, it was found that 50% of respondents climbed wind turbines four to six days per week. The median turbine height climbed was 36 m whilst carrying external loads up to 15 kg. Finally, only 25% of wind turbines they climbed contained climb assist devices.

This thesis ascertained that vertical ladder ergometer climbing was significantly ($p < 0.05$) more demanding than pitched ladder climbing with large effect on $\dot{V}O_2$ ($d = 1.7 – 3.3$) and heart rate (HR)($d = 1.5 – 1.9$). The change in pitch lead to the mean $\dot{V}O_2$ across all speeds increasing from 39.1 $ml.kg.min^{-1}$ to 45.5 $ml.kg.min^{-1}$ and mean HR increasing from 148 bpm to 170 bpm.

The use of a climb assist device significantly ($p < 0.05$) decreased mean $\dot{V}O_2$ from 28.3 $ml.kg.min^{-1}$ to 22.0 $ml.kg.min^{-1}$, mean HR from 134 bpm to 114 bpm and the rate of perceived exertion (RPE) reduced from a median of 3 to a median value of 1. Furthermore, descending a vertical ladder has a significantly lower energetic cost than that of ascending with a significant ($p < 0.05$) decrease in $\dot{V}O_2$ from 28.3 $ml.kg.min^{-1}$ to 15.3 $ml.kg.min^{-1}$, mean HR from 134 bpm to 111 and the rate of perceived exertion (RPE) reduced from a median of 2.5 to a median value of 1. Climbing vertically with 5 kg significantly increased $\dot{V}O_2$ (36.4 v. 38.1 $ml.kg.min^{-1}$) and HR (162 v. 167 bpm) compared to a no-load condition and climbing vertically with 10 kg also significantly increased $\dot{V}O_2$ and HR compared to no load (36.4 v. 40.1 $ml.kg.min^{-1}$; 162 v. 170 bpm) and 5 kg condition (38.1 v. 40.1 $ml.kg.min^{-1}$; 162 v. 170 bpm). There was no significant ($p > 0.05$) change in the horizontal space required for climbing when a space constraint (0.88 m, 1.03 m or 1.23) was applied to participants compared to an unrestricted condition.

This thesis found that depending on the speed and/or the presence of an external load that the intensity of vertical ladder ergometer climbing exceeds that of the medical fitness guidelines. In doing so this thesis proposes future work should re-examine the medical fitness standard and highlights that more research in order to create an evidence base from which to design a bespoke industry fitness standard.

Keywords: Ladder climbing; Vertical Ladder climbing; Ladder ergometer; External load; Climb assist; Restricted space; Physical Employment Standard.

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Publications

Published peer reviewed articles

BARRON, P.J, et al., 2017. The physiological effect of a 'climb assist' device on vertical ladder climbing, Ergonomics, 60 (7), pp. 1008-1013.

BARRON, P.J, et al., 2018. The effect of pitched and vertical ladder ergometer climbing on cardiorespiratory and psychophysical variables, Applied Ergonomics, 66, pp. 172-176.

Conference Proceedings

Barron, P.J., et al., 2017. The impact of load carriage on vertical ladder ergometer climbing. 22nd annual conference of the European College of Sport Science, p.65-66.

List of Abbreviations

ANOVA	Analysis of variance
BMI	Body mass index
COM	Centre of mass
EMG	Electromyography
FFM	Fat free mass
GWO	Global wind organisation
HR	Heart rate
KPM	Kilopond meters
MEMG	Maximal electrical myography
MW	Megawatt
PARQ	Pre activity readiness questionnaire
PES	Physical employment standard
PPE	Personal protective equipment
RPE	Rating of perceived exertion
UKFRS	United Kingdom Fire and Rescue Service
$\dot{V}O_2$	Volume of oxygen

1.0 Introduction

The introduction of the Paris agreement indicated a near global commitment to reducing climate change and a shift towards renewable energy due to the requirement to reduce carbon emissions (Briggs 2017). Since 2001 there has been an increase in the global installed wind energy capacity from 23.9 GW up to 539.1 GW with global annual installations exceeding 51.6 GW since 2014 (GWEC 2017). Within Europe since 2013 there has been a steady increase in the annual installed wind energy capacity with 16.8 GW being installed in 2017, as 3.2 GW of offshore and 13.6 GW onshore energy (GWEC 2017). Global forecasts suggest that there will be a continual rise globally in total wind energy output up until 2040 (Renewable UK 2018a).

In order to meet the demand in installations, it would be expected that the number of employees required throughout the supply chain would have to increase. In 2014 the number of those working in the industry within the UK had risen to 19,000 and is forecast to double by the early 2020's (Renewable UK 2018b). As the number of individuals employed in the wind energy industry increase they will be required to undertake testing aligned to the Renewable UK (2013) medical fitness to work guidelines. This document outlines the unique nature of the wind energy industry by highlighting hot ambient conditions, confined space and the exertion required to climb up to 80 m vertically in the event of a lift failure to reach the turbine nacelle (See Figure 1.1).

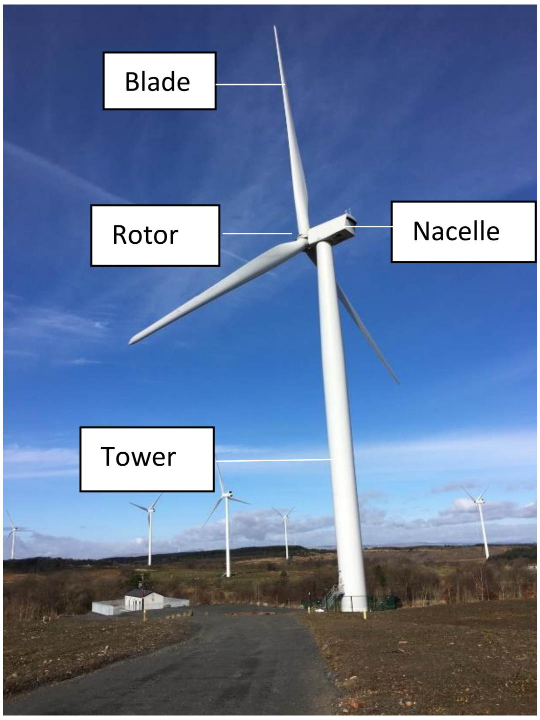

Figure 1.1 Labelled wind turbine

The medical fitness to work guidelines outline that in order to be deemed physically fit to climb an individual must achieve an estimated $\dot{V}O_2$ max of greater than 35.0 $ml.kg.min^{-1}$ (Renewable UK 2013).

The suggested method of assessing $\dot{V}O_2$ max is by a shuttle run test or the Chester step test rather than by direct measurement (Renewable UK 2013). Further to this the value previously stated is said to be based on normative data however, to date no literature has been published on the demands of climbing long vertical ladders. Whilst such data may exist without it having gone through the peer review process such data may not be considered robust. Research conducted by Peterson et al. (2016) sees the role of peer reviewed published literature as a measure of credibility in the context of physical employment standards (PES) if legally challenged. Therefore, with currently no published research in such a field and the projected growth in the industry a deeper understanding of the field is critical.

Several different tasks were outlined as important within the medical fitness to work documents (Renewable UK 2013). These were vertical ladder climbing and working in confined spaces. If taken in isolation the current understanding of vertical ladder climbing within published literature is lacking. Whilst ladder climbing appears to be a central point within the medical fitness documentation as it is the only area of the guidelines which is deemed important enough to assign a cut score to. Anecdotal evidence (McCaul, J., personal communication conversation 2015) suggested that this value was recycled from another industry and that altering the value would be of use to the industry. Therefore, this suggested that the current value was not truly reflective of the nature of the industry. The physical exertion required to climb a wind turbine is not currently known and research should aim to understand the demands of vertical ladder climbing to relate to this growing industry.

1.1 Aims and Objectives

The aim of this thesis was is to gain a greater understanding of the wind energy industry and its current practises. A secondary aim was to ascertain the physiological and psychophysical demands of ladder climbing in to order understand whether these are in line with the current medical fitness guidelines (Renewable UK 2013).

Based on the two previously stated aims several objectives were borne out of the above aims:

1. Gain a greater understanding of the day to day practices of wind turbine technicians to base future research on
2. Ascertain whether the demands of pitched ladder ergometer climbing differ from vertical ladder ergometer climbing
3. Understand the effect that industry specific conditions can have on the demands of ladder climbing such as the effect of external loading, climb assist or space constraint

It was hypothesised that the measured demands of ladder climbing will exceed that of the current medical fitness guidelines of 35 ml.kg.min^{-1}. It was also hypothesised that the addition of external loading will significantly increase the demand of ladder climbing and the use of climb assist devices would reduce the demands of ladder climbing. Finally, it was also hypothesised that the demands of vertical ladder ergometer climbing will be significantly larger than that of pitched ladder ergometer climbing.

As highlighted in the aims and objectives this thesis aimed to understand the current practices of the wind energy industry and from there gain an understanding of the demands of ladder climbing. The initial literature review focussed around the current medical fitness guidelines and training standards to understand the role. At this point it was seen that ladder climbing is a task of key importance and it was the only factor considered with the medical fitness documentation assigned a cut score (Renewable UK 2013). It was therefore taken that this was a key task which has subsequently been ratified by Milligan, O'Halloran and Tipton (2018). An initial narrative literature review took place investigating occupational physiology, physical employment standards and ladder climbing (Section 2.0). At this point numerous questions still existed around the role of wind turbine technician and this led to the undertaking of a survey (Chapter 3.0) with the objective of understanding the day to day role of a wind turbine technician and provide an evidence base to design future research from. The results from this highlighted that 60% of turbine technicians reported climbing 4 to 6 days per week with the median turbine height reported being 36 m. It was also reported that individuals could climb with external loads up to 15 kg in a climbing bag with 5 kg also reported. Climb assist systems were only reported to be in turbines by 25% of study participants and that the tasks they performed in the turbine differed from on the ground due to space constraints. Furthermore, 37.5% of participants reported they sometimes felt restricted by the shape of wind turbine when climbing, which was also anecdotally reported by participants in section 6.0. At this time-point, the newly-commissioned RGU ladder ergometer had been installed and was fully operational before being modified to be vertical (approximately 18 months from commencement). Therefore, based on the survey results three avenues had potential for research to be conducted either practically or based on opportunities with industry. These three avenues were climb assist, external loading and space restriction.

Between the time of the commencement of the survey and the commencement of the external loading and space restriction study there were three studies which took place. Firstly, the reliability study based on the ladder ergometer arriving and aiming to understand the reliability of the physical measures that may be used during the future studies ($\dot{V}O_2$ and heart rate (HR)) and understanding whether there was any learning effect seen on these. It was found that lower speeds showed improved relative reliability with a smaller SEM compared to faster speeds and that coefficient of variation (CV) reduced over time. This informed future studies by suggesting that research should be conducted at lower speeds and that familiarisation sessions were beneficial. This study took place at a pitch of 75° but was not able to be replicated once the ergometer was modified to vertical due to time constraints.

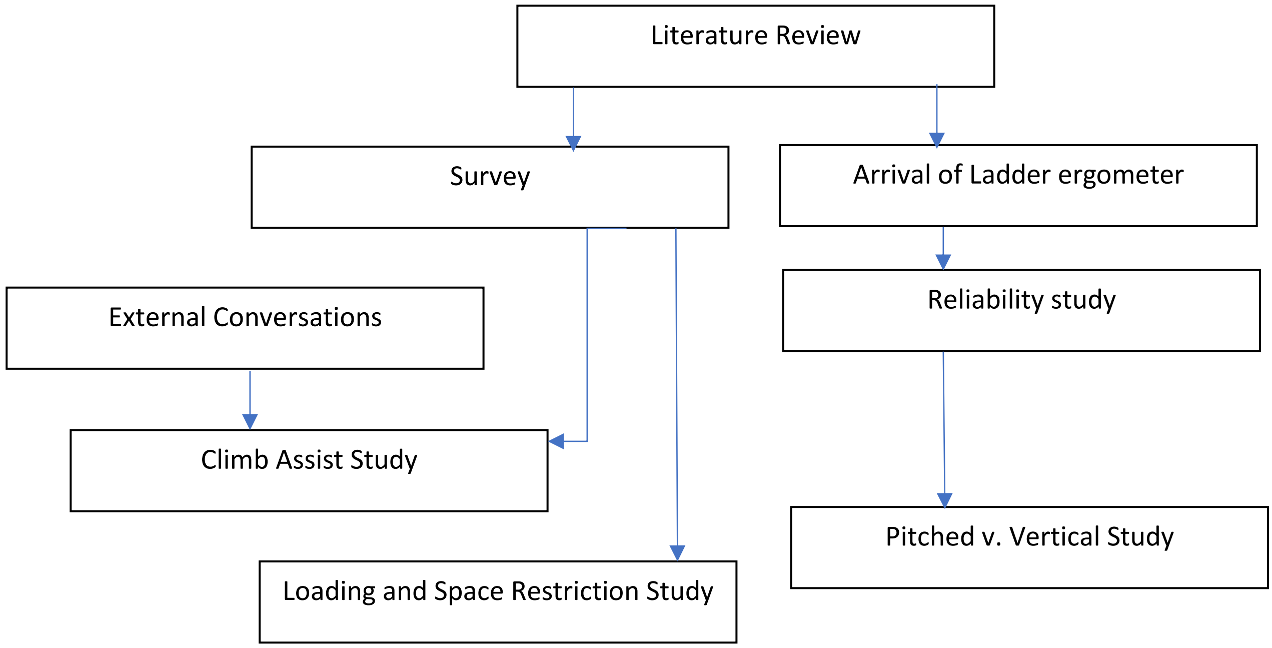

Figure 1.2 Thesis overview

Whilst the reliability study was ongoing, and the survey results were being processed an opportunity arose to run a study based on the effect of a climb assist device (Section 6.0) at a working at height testing centre. This opportunity combined with the survey results allowed for a novel in-situ investigation of the effect of a climb assist device on physiological and psychophysical variables. The study was designed based on climbing rates from literature (Milligan 2013) and was a one-day data collection session with experienced ladder climbers. The results of this study highlighted that the use of a climb assist device significantly ($p < 0.05$) reduces mean $\dot{V}O_2$ from 28.3 $ml.kg.min^{-1}$ to 22.0 $ml.kg.min^{-1}$, mean HR from 134 bpm to 114 and the rate of perceived exertion (RPE) reduced from a median of 3 to a median value of 1. A secondary aim of this study was to ascertain the difference between ascending and descending a ladder as this had not previous been investigated within the literature. It was observed that descending a vertical ladder has a significantly lower energetic cost than that of ascending with a significant ($p < 0.05$) decrease in $\dot{V}O_2$ from 28.3 $ml.kg.min^{-1}$ to 15.3 $ml.kg.min^{-1}$, mean HR from 134 bpm to 111 and the rate of perceived exertion (RPE) reduced from a median of 2.5 to a median value of 1. During this study the reliability study was still on going and discussions were taking place to modify the ladder ergometer.

Upon completion of the reliability study the ladder ergometer was modified to vertical requiring the construction of a wedge and recalibration of the ladder ergometer to vertical. This allowed for the opportunity to conduct an experiment assessing the difference between vertical and pitched ladder ergometer climbing at matched vertical climbing rates. This has large relevance to the application of the current medical fitness guidelines which were recycled from the UK Fire and Rescue service who use pitched ladders rather than vertical ladder as in the renewable sector. Further to this it would inform whether it is appropriate to compare pitched and vertical climbing studies. It was found that vertical ladder ergometer climbing was significantly ($p < 0.05$) more demanding than pitched ladder climbing with large effect on $\dot{V}O_2$ ($d = 1.7 – 3.3$) and heart rate (HR)($d = 1.5 – 1.9$). The change in pitch led to the mean $\dot{V}O_2$ across all speeds increasing from 39.1 $ml.kg.min^{-1}$ to 45.5 $ml.kg.min^{-1}$ and mean HR increasing from 148 bpm to 170 bpm. Therefore, it was deemed that basing a fitness standard from research or an industry using pitched ladders was not appropriate.

The last study to be conducted was the external loading and space constraint study (Section 7.0) which was based on the outcomes of the survey identifying these as two factors that could impact performance and that could be practically investigated in a laboratory situation. The results showed that climbing vertically with 5 kg significantly increased $\dot{V}O_2$ (36.4 v. 38.1 $ml.kg.min^{-1}$) and HR (162 v. 167 bpm) compared to a no-load condition and climbing vertically with 10 kg also significantly increased $\dot{V}O_2$ and HR compared to no load (36.4 v. 40.1 $ml.kg.min^{-1}$; 162 v. 170 bpm) and 5 kg condition (38.1 v. 40.1 $ml.kg.min^{-1}$; 162 v. 170 bpm). There was no significant ($p > 0.05$) change in the horizontal space required for climbing when a space constraint (0.88 m, 1.03 m or 1.23) was applied to participants compared to an unrestricted condition.

This thesis highlights the need for further investigation into the role of a wind turbine technician and the demands placed upon them. Furthermore, it would suggest that the current fitness standard should be re-examined and due consideration be given to the impact of external factors that can positively and negatively influence the physical strain placed on individuals.

2.0 Literature Review

2.1 Occupational Fitness Standards

The field of occupational fitness is complex with the methods of researching, designing and implementing a fitness standard for employees recently evolving (Tipton, Milligan and Reilly 2013, Petersen et al. 2016). There has been a need to formalise the development of such standards due to the necessary requirement for such standards to be legally defensible when challenged in a court of law (Petersen et al. 2016). As such there has been a shift to developing standards from a peer reviewed evidence base such as the work conducted by Reilly, Wooler and Tipton (2006), Reilly et al. (2006), Siddall et al. (2014), Milligan (2013) and Blacker et al. (2015). Fitness standards require the passing of a test whether it be a cut score on an assessment or passing a pass / fail test in order to provide some level of assurance that an individual is safe to work. Traditionally occupational fitness standards were viewed as physiological standards, commonly a $\dot{V}O_2$ max value, to be assessed either by direct measurement or a predictive test, such as the shuttle run or the Chester step test (Renewable UK 2013). As an alternative to this, many industries have considered or implemented task-based occupational fitness standards which are specifically researched, designed and tailored to the needs of demands of their organisations (Tipton, Milligan and Reilly 2013).

Occupational fitness standards such as these are derived from critical, criterion, generic or essential tasks which are required to be safely undertaken and completed. In the UK, the military, RNLI and Oil and Gas UK have all developed or implemented an occupational task-based fitness standard (Rayson, Holliman and Belyavin 2000; Reilly, Wooler and Tipton 2006; Reilly et al. 2006; Energy Institute 2010). These standards may be implemented for numerous reasons including: undertaking specific task simulations; provide a robust, valid and reliable physical employment standard (PES) connected to a required role; they provide a duty of care; and allow for a discriminatory free standard (Tipton, Milligan and Reilly 2013; Petersen et al. 2016). It must be recognised there are potential barriers to implementing such PES. These may include the timescale, potential cost and the complexity of developing such a standard with the justification having to come from robust peer reviewed research. Research within occupational fields has tended to focus on physically demanding professions with critical task-related outcomes such as the police and fire and rescue service. This raises a concern that whilst many industries have PES, only a handful of industries have research conducted within them to this aim. Although this does not mean such research has not been conducted, rather that is has not been published through the peer review process. Peer reviewing research provides credibility, aids in the enhancement of knowledge and allow for the wider widely benefits to the scientific community (Petersen et al. 2016). If such research exists and is not in the public domain, this hinders the advancement of practice and wider knowledge. The referencing of such research or normative data in documents without peer review casts doubt over any values or decisions based on it. An example of this is Renewable UK (2013) who recommend a cut off score for $\dot{V}O_2$ max based on normative data. However, no research has been published specifically tailored to this unique industry or the critical task within it. Whilst this normative data may exist within industry, failing to take the step to the public domain and peer review limits the credibility of such data and the cut off score derived from it. Furthermore, it leads to an impression that there is little justification for the chosen cut score. Only a handful of industries have adopted a task-based occupational standard, and recent literature recognised that a method of best practice for developing and implementing such standards needs to be defined (Peterson et al. 2016).

The advent of PES is not a recent development and standards have been researched over several decades with the emphasis being placed on occupations that are physical in nature whilst undertaking tasks which may be critical. Researchers have considered different simulated tasks in order to find out the demands of the roles, however, this does not often translate into defining a required threshold score for a physical aptitude test. Only recently has literature described the method of best practice for developing a PES with Tipton, Milligan and Reilly (2013) initially providing a model. This was subsequently built on by Petersen et al. (2016) who highlighted twenty steps within a framework for developing a PES. This approach requires a combination of both academic and industry input alongside those currently performing the role in order to develop a standard. Therefore, it is understandable, as recognised by Petersen et al. (2016) that companies or industries may wish to recycle a standard from a seemingly similar industry due to convenience, as well as cost and time reduction. However, this method is often inappropriate as the roles and tasks performed are often not identical between industries. When an industrial recycles a PES the minimum cut score for a given test should be modified to reflect the different role however, this does not always occur. An anecdotal example of this is recommended cut score of 35 $ml.kg.min^{-1}$ for a $\dot{V}O_2$ from Renewable UK, which is reported to be recycled from the UK Fire and Rescue Service (UKFRS). While the employees of both professions climb ladders, the similarities end there and fundamental differences exist between the industries making it inappropriate to recycle this standard to Renewable UK. Examples of these fundamental differences are pitched v. vertical ladders; the different types of PPE used; the difference in vertical height gained; different physiological demand; and the external loads carried and the position of these loads. Therefore, it would be appropriate to re-examine the renewable energy sector in order to aid in the development of a more appropriate PES.

Over the past twenty years there have been significant changes and developments in the development of physical employment standards with an increased shift towards involvement and coordination between both the academic and industry bodies (Reilly, Wooler and Tipton 2006; Reilly et al. 2006; Siddall et al. 2014; Milligan 2013; and Blacker et al. 2015). The shift towards increased academic input leads to the existing research being critically appraised to create fitness standards based on peer reviewed academic literature. Whilst this is visible in work conducted by Milligan (2013), Energy Institute (2013) and Reilly et al. (2006) for both RNLI and Oil and Gas UK fitness standards, this has not been replicated by Renewable UK. The most recent health and safety documentation for onshore wind available from Renewable UK (2013) acts as a guideline for the assessing medical fitness and suggests that employers must ensure that any physical aptitude test should be specific to the tasks which are performed. This is consistent with the literature ensuring that tests are a valid assessment of a role (Petersen et al. 2016). The Renewable UK medical fitness to work guidelines (2013) outline areas which can be examined as part of a health assessment prior to employment. These areas range from vision assessments to the physical capability to climb ladders. Renewable UK outline this document as a guideline and that the areas highlighted should be assessed, as any issues highlighted could compromise safety of an employee or others around them. Furthermore, they outlined that those who climb vertical ladders on a regular basis should have an estimated $\dot{V}O_2$ max of 35 $ml.kg.min^{-1}$ (Renewable UK 2013). This value is based on non-peer reviewed normative data most likely from a different occupational group and was not determined experimentally with vertical ladder climbing. To date there is currently limited research assessing the demands of vertical ladder climbing.

2.2 Ladder Climbing Research

Ladder climbing in various forms has prevailed for hundreds of years and currently ladder climbing takes place in many industries for instance the fire and rescue service, oil and gas, renewable energy and crane driving. Although the exercise modality is the same it is expected that each individual industry would have its own unique demands based on several factors including ladder pitch, length, PPE and environment. All of these factors could affect the demands placed on individuals when ladder climbing. Furthermore, it highlights the breadth of literature required to be considered when developing a fitness standard due to the number of factors related to the industry and ladder climbing Taking the overall picture of ladder climbing literature over the past 50 years it is clear to see different pathways of literature development have occurred (Figure 2.1).

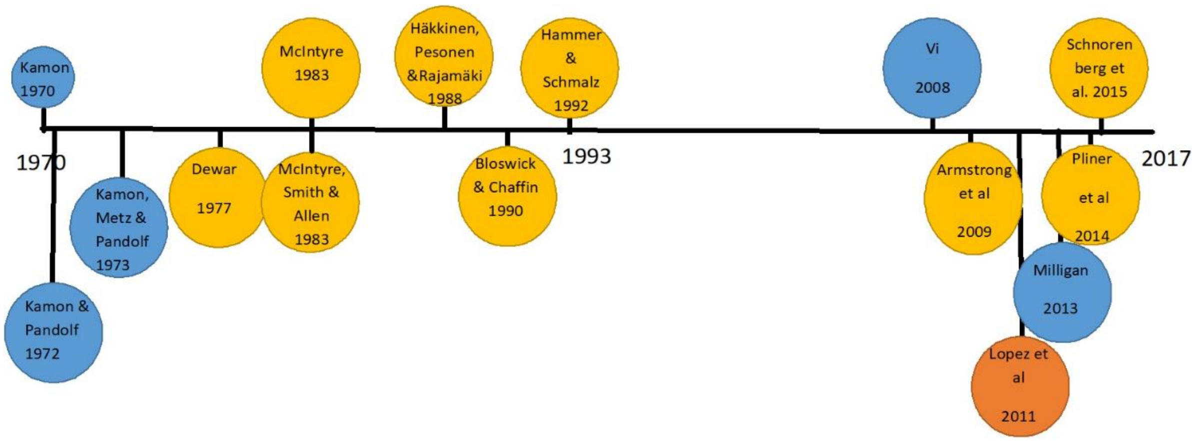

Figure 2.1 Timeline of ladder climbing research*

* Blue- Physiology, Yellow- Biomechanics, Orange- Health and Safety (Not to scale)

This has in part been driven by various industries and it was suggested by Lopez et al. (2011) that the research direction into biomechanics was driven by the increasing insurance payouts in the United States of America due to accidents on ladders. Whilst the current understanding of ladder climbing today is derived from the work conducted over the past five decades. Therefore, it is necessary to understand the current literature base before deriving a fitness standard for a potential ladder climbing based occupation. This is important to see the relationship, or lack of, to the requirements of climbing modern day wind turbines from research generally conducted pre-2000 which predates the first UK. The literature highlighted in figure 2.1 was grouped within three overarching areas and within each of these the focus for the research varied on topic and enviroment used. The limited research within each area and the broad nature of the research within these areas meant that a systematic review was not appropriate. Whilst there is no minimum number of articles for a systematic review the research question should be clear and clinical with specific reference to the outcomes to be investigated (Wright et al. 2007, Charrois 2015). Applying a specific research question this to the limited literature base within specific areas would yield a small number of articles of which would lack the quality or specificity to be considered. The use of a narrative review allows for a broader anaylsis of a literature body that covers numerous areas and subtopics within each the areas of physiology, biomechanics and health and safety.

2.3 Early ladder climbing research (1970s)

Early ladder climbing research undertaken at the beginning of the 1970s centred on understanding the demands of pitched ladder ergometer climbing either at 60° or 80° (Kamon 1970; Kamon and Pandolf 1972; Kamon, Metz and Pandolf 1973). Kamon (1970) aimed to understand the difference in energy cost between ascending and descending a ladder ergometer using the foot over foot climbing style. The basis for this research was that step tests, such as the Chester step test were used to determine fitness and that the mechanical work of stepping down from the stool was ignored or the assumption was made it was like walking up or down a hill (Kamon 1970). The study (n = 4) used a range of vertical climbing speeds (4 – 35 m per minute) to ascertain the cost of ascending and descending a ladder ergometer. Participants completed five-minute bouts of climbing interspersed with 20 to 30 minutes recovery. Heart rate (HR) and $\dot{V}O_2$ consumption was measured during the final minute of ascending and the final two minutes of descending. The interpretation of the results showed that descending the ladder ergometer had an average net $\dot{V}O_2$ of 26% of the value compared to ascending, although the raw $\dot{V}O_2$ values were not reported. The study does not state how many speeds participants undertook or the exact speeds at which they climbed although two participants completed approximately 11 speeds for ascending and descending. Kamon (1970) did not outline mean results for the overall sample size but did highlight the mean $\dot{V}O_2$ results for three speeds for the male participants. This makes repeating the study impossible because the exact protocol was not stated. This study did, however, show that at 60° ascending a ladder ergometer incurs a greater oxygen cost than that of descending. However, the small sample size and the limited scope of the raw data and imprecise protocol suggest that more research was needed to clearly understand the demands of ladder climbing.

Kamon (1970) made comparisons between varying exercise modalities when investigating ascending and descending a ladder ergometer which led to work being conducted in comparing maximal aerobic power between several exercise modalities (Kamon and Pandolf 1972). Kamon and Pandolf (1972) suggested that the maximal aerobic power ($\dot{V}O_2$ max) was determined by muscle mass recruitment and that increased lower limb muscle recruitment yielded higher $\dot{V}O_2$ max values. They hypothesised that due to the increased recruitment of the arm muscles in proportion to climbing rate, that ladder ergometer climbing would produce higher $\dot{V}O_2$ values compared to that of uphill running and cycling. This was due to these two latter exercise modalities predominately recruiting leg body muscles (Kamon and Pandolf 1972). The participants for the study were from three distinct groups with A being non habitual exercises (N= 3, 1 m and 2 f); B being habitual exercisers approximately 1 or 2 times per week (N= 11, 5 m and 6 f); and group C participated in 3 to 4 vigorous training sessions per week (N= 9, 5 m and 4 f). Participants completed either submaximal or maximal aerobic tests in the three previously mentioned exercise modalities. The protocol used by Kamon and Pandolf (1972) required participants to run on a treadmill graded at 10% at 7 mph for males and 6 mph for females for 3 minutes and expired air collected between 1 minute 45 s and 2 minutes 45 seconds. Participants repeated this on consecutive days with the treadmill gradient being increased 2.5% per day until $\dot{V}O_2$ max changed by less than 2.1 $ml.kg.min^{-1}$ between days. The authors provided no justification for this value. For the cycle ergometer test, all cycling was completed at 60 rpm and ladder climbing took place on a motorised ladder ergometer at 60°. The methods of assessing maximal aerobic power for climbing and cycling differed within the participants. Nine participants completed one method of assessment and 14 undertook an alternative method. The first method required participants who had previously completed submaximal studies by the research group to commence climbing or cycling at a rate predicted to elicit $\dot{V}O_2$ max for 3 minutes based on prior test results. If participants completed the 3 minute exercise bout, the workload was increased for the next testing session by 90 kg/m/min until there was less than a 2.1 $ml.kg.min^{-1}$ change in $\dot{V}O_2$ max for a work load difference of 180 kg/m/min. The translation of these workloads is difficult to ascertain for both cycling or ladder climbing. Kamon and Pandolf (1972) did not translate these workloads into either a change in speed for ladder climbing or an increase in power output or cycle ergometer load clearly. Both the incremental work load (kg/m/min) and the calculated work load (Kilopond meter/minute) (are not a recognised systeme internationale (SI) unit and therefore makes the understanding and generalisation of the workload problematic (Winter and Fowler 2009). The alternate method (n = 14) of estimating the workload to achieve $\dot{V}O_2$ max was based on the value during the uphill running test. The value achieved for this was inputted into regression equations (Kamon and Pandolf 1972 p. 468), based on previous work (Kamon 1970), which was used to determine the initial workload for the different modalities. If the participants completed a three-minute bout of cycling or climbing they returned on subsequent days where the workload was increased. If they failed to complete a three-minute exercise bout on the first testing day the workload was reduced. Kamon and Pandolf (1972) do not state by how much the workload was altered for either modality or when the final cut off was, but it could be assumed the same protocol was used as per the first method of altering the work load. This testing protocol for all modalities would now be considered outdated with participants currently undertaking a single maximal test on one day such as a continuous ramp protocol (Australian Institute of Sport 2013). The protocol used by Kamon and Pandolf (1972) could therefore lead to residual fatigue affecting results as participants were required to perform repeated near maximal efforts on consecutive days. The results showed that in the male group, $\dot{V}O_2$ max was significantly higher for both running ($p < 0.001$) and ladder ergometer climbing ($p < 0.01$) (54.84 and 52.71 $ml.kg.min^{-1}$) compared to cycling (48.61 $ml.kg.min^{-1}$). Further to this a significant difference ($p < 0.05$) was observed within overall male group between uphill running and ladder ergometer climbing. Within the male group no differences were observed between exercise modalities for the inactive or the trained group when $\dot{V}O_2$ was scaled to body mass. By contrast the female group showed no overall difference between running and climbing (44.3 v. 45.1 $ml.kg.min^{-1}$) however, both were significantly higher than cycling (41.2 $ml.kg.min^{-1}$). These results were also found in the active female group, but no significant differences were observed in the habitual and non-habitual exercise groups. The method of statistical analysis used was not stated and therefore it is unknown whether for instance they used a one-way analysis of variance (ANOVA) with Bonferroni post hoc test to ascertain main effects or whether a repeated paired t test was used which could inflate type I error. This means that although the trends in the results may be generalised the data should be interpreted with caution. As alluded to by Kamon and Pandolf (1972), it was hypothesised that ladder climbing would yield a greater $\dot{V}O_2$ max that of cycling due to the increased muscle activity in climbing with a mean difference of 11% in $\dot{V}O_2$ max. Such knowledge should be then used when conducting fitness tests, because as the effective ceiling imposed by cycling may not allow for participants to achieve their true maximum, which will be critical if the 11% difference between ladder climbing and cycling also spans the occupational test threshold. This work adds to the sparse picture of ladder climbing and highlights where, in the continuum of exercise it sits, and how it compares against other modalities.

Building on the work previously mentioned, Kamon, Metz and Pandolf (1973) investigated whether cycling or cycling with additional weight on limb extremities altered the energy cost of movement. The rationale was based on ascertaining a proportional rise in $\dot{V}O_2$ compared to the load but also whether situations with extreme load or training with additional load altered the energy cost. Whilst the basis for the research was not driven by industry *per se*, the relevance of such a study to industry is clear, in terms of the relationship between increased O_2 demand relative to the increased load. Fourteen male participants completed ladder ergometer climbing at 80° at three speeds (7.5, 10.5 and 14.0 m per minute) and ergometer cycling at a comparable load, which was calculated from the workload (kpm/min) from the ladder ergometer climbing. The cycling was then conducted at 50 and 75 rpm controlled using an electronic metronome. Participants completed nine testing days with 21 work bouts across these three days with two to three five-minute exercise bouts per day with each bout being separated by 15-30 minutes of recovery. Participants were assessed for ladder climbing with no load, 5 kg and 10 kg attached in three loading locations: around the waist; around the ankles; and around the ankles and waist. The results suggested that there was a difference in oxygen uptake between the unloaded condition and loading on the extremities but not when loading at the waist. However, no difference was observed between waist, ankle and ankle and wrist loading conditions. There are several potential factors for this with the authors citing that there is large variability in the data which could affect results and “poor uniformity” (Kamon, Metz & Pandolf 1973 p. 369). Further analysis in the ANOVA highlighted that there was a significant difference in presumably $\dot{V}O_2$ between the slowest and fastest speed in all loading conditions and also between the slow and medium speeds for no load only. Only one loading condition showed a change from no load and that was ankle loading at the medium speed. It should be recognised that no mean data were published for ladder ergometer loading at any speed with only regression graphs and confidence ellipses being published. This makes it very difficult to make inferences on the effect of loading as the study is potentially underpowered with the main analytical test a three factor ANOVA. The recruitment of 14 participants was unlikely to be sufficient to power the study. The discussion provides more clarity noting that external trunk loading leads to a similar energetic cost of climbing when scaled to body mass and does not disproportionately increase the energy cost of movement. However, they note this observation is speed dependent with higher speeds increasing the oxygen cost when trunk loaded compared to unloaded. The authors recognise that by splitting the loading across the extremities may reduce the impact as there is not enough individual stimulus on each limb in which to trigger a significant increase oxygen cost. Despite the novel study design, its limited ability to detect an effect means its conclusions cannot be relied on.

The basis of ladder climbing physiology is grounded in these three aforementioned articles despite their identified limitations have laid the foundations for the limited understanding of ladder climbing. They highlight and provide the required impetus that future research should be more robust in this area. They showed that climbing upwards has a greater oxygen cost compared to descending, ladder ergometer climbing is comparable or has lower energy expenditure compared to uphill running and that loading the extremities has no effect on ladder climbing energy cost. Since 1973 there was a change in emphasis on research into understanding the technical aspects of ladder climbing rather than the physical demands.

2.4 A shift to biomechanics- research from 1977-1993

Whilst early work investigated the energy cost of pitched ladder ergometer climbing however, for various reasons (Kamon 1970, Kamon and Pandolf 1972 and Kamon, Metz and Pandolf 1973) after 1977 there was a deliberate shift in the research focus to the biomechanics of ladder climbing. Dewar (1977) identified that the mechanics of moving the body's centre of mass vertically upwards was not known, therefore ascertaining how this was done was of scientific interest and curiosity. Dewar (1977) was also the first article within this field to be informed by practice rather than solely scientific curiosity. Undertaking research into the movement of the body during ladder climbing could be applied to understanding the factors affecting accidental ladder slippage in the work place. Dewar (1977) estimated that approximately 34% of ladder related accidents occurred due to stumbling or misplacing hands and/or feet when climbing. He pursued this avenue because the angle of the ladder climber and the angle of ladder may have been two key factors contributing to ladder climbing errors. Participants (n = 35) with nine having been given previous ladder climbing instruction and 14 never having received instruction or previously having climbed a ladder. Participants completed two ascents and descents of a wooden 4 m ladder with rung spacing of 25.5 cm at pitches of 75.2° and 70.4° with seven markers placed on the right ankle, knee and hip, each at the estimated centre of rotation, right iliac crest, sacrum (mid dorsal line), C7 vertebra (mid lateral line) and the lateral aspect of the head of the ulna (Dewar 1977). During the climb participants were video recorded from the right-hand side, providing a view of the sagittal plane of participants. A mirror was also placed at the point where the y axis and the optical line of the mirror met to provide a rearview mirror image of the ladder climber. At all times from both planes of view an object of a known dimensions was within the field of view as a reference point. The results from this study informed one of the first publications to describe the biomechanics of ladder climbing, in this case recognising it as a symmetrical cyclical action similar to walking. Dewar (1977) does not provide a breakdown of the number of participants and the related movements of the hand and foot relationship, however, he recognises that there are two different techniques: diagonal and lateral gait. Diagonal gait is where the opposite hand and foot move together in contrast to lateral gait which is the same sided foot and hand moving simultaneously. Dewar (1977) reported that diagonal gait was the most commonly used technique. Furthermore, he also put forward that holding the rails was more common when climbing, as opposed to the rungs, however, again no data were presented. This data was not presented as some participants had previously been provided with technical ladder climbing instructions. Therefore, the results may not have represented their natural climbing gait but rather the instructed gait. Dewar (1977) found no significant differences ($p > 0.05$) in contact or stride time between the two ladder pitch angles. Although the ladder pitch changed, the speed at which participants moved along the ladder did not significantly change. Furthermore, at both pitches as the stride time decreases the contact time decreases near proportionally. This was deemed to occur as a constant stride length was maintained due to the fixed position and distance of the rungs. This work provided several descriptions of joint angles and movement profiles which helped create the basic understanding of ladder climbing. When this research was conducted little was known about ladder climbing biomechanics and whilst Dewar (1977) mentions briefly the effect of ladder pitch and the relationship between pitch and ankle-sacral anterior displacement. This indirectly highlighted the effect of ladder pitch on the centre of mass, although consideration needs to the given to the angle of the trunk as this will also affect the centre of mass, not solely the position of the sacrum. Dewar (1977) suggested that the hands potentially contribute more to maintaining balance and at a steeper angle if a hand slip occurred the consequences of losing balance could be more serious. These previously mentioned points, whilst correct also did not acknowledge the decrease in the size of the base of support. Although Dewar (1977) recognised the feet as support, as the horizontal distance between the hands and feet is reduced there would be impact on mechanical load. Further insights included that whilst ladders were designed and built for the “average” man those at the extreme ends of stature, both tall and short, showed a tendency towards different peak knee flexion angles. Secondly their timing differed appreciably within a stride compared to the average (Dewar 1977). This suggests that smaller individuals had to raise their ankles higher relative to their stature to reach the next rung, and this potentially increased the mechanical work completed. At the time, this work conducted by Dewar (1977) was the first study to investigate the biomechanics of ladder climbing. It increased the knowledge of ladder climbing but there could have been a more detailed analysis on gait and technique of ladder climbing undertaken.

Whilst Dewar (1977) provided an initial overview of ladder climbing, over the following 15-year period, there was a large increase in research surrounding the biomechanics and techniques in ladder climbing. Moving forward within the 1980s research, McIntyre, Smith and Allen (1983) focussed on understanding the potential risk factors with ladder accidents in the United States of America. He postulated that the type of footwear worn would impact flexion at the foot and the forces produced, which could impact on slippage if the force produced was at the point of maximum dorsiflexion. Fourteen male participants climbed a 75.2° ladder with rung spacing of 30.48 cm at a comfortable pace with high top and low tops work boots as well as barefoot. The length of the ladder was not stated but strain gauges were fitted to the ladder rungs. A video camera was set up to record the climbing bouts from the right side of the body for the analysis of joint angles. The results showed that climbing barefoot lead to significantly greater dorsiflexion compared to wearing boots. However, there was no significant difference between the high and low top boot conditions. Further to this, the points of maximum force coincided with the point of maximal dorsiflexion where slips are most likely to occur. This study was very focussed on understanding the effect of footwear and could inform future work on the types of footwear to be used within research studies.

Following on from this work McIntyre (1983), again with a focus on accidents, aimed to ascertain the different types of gait adopted when ladder climbing. This work aimed to develop on the work conducted by Dewar (1977) who found the most common gait to be the diagonal gait. However, this was in part due to the fact they only counted those who had never received ladder climbing instruction. This was because those who had done so climbed in the lateral gait which would inevitably have biased the results. Twenty-four male participants climbed a 75.5° ladder five times at a comfortable pace with the 1st, 3rd and 5th trials recorded for analysis using both video and touch pads on the rungs. McIntyre (1983) found that unlike Dewar (1977) the lateral gait was the most commonly used technique across all three trials (30.3%) and four beat lateral gait was the second most common technique used. These values were much higher than those for diagonal (15.2%) and four beat diagonal gait (18.2%). This was the first report of ‘four beat‘ techniques which was defined by McIntyre (1983) as the movement sequence of right leg, right arm, left leg and left arm for lateral four beat. Four beat gaits do not demonstrate the same characteristics as two beat gaits because there are never four points of contact on the ladder however, there is greater time where three points of contact are in place on the ladder throughout one complete cycle. This would provide the greater likelihood of preventing a fall should a slip occur due to three points of contact versus two points of contact.

Based on this research a case could have been made for the teaching of a four-beat gait as this encourages greater contact time with the ladder and could minimise the risk accidents. The use of multiple trials showed that only 31.8% of individuals maintained the same gait throughout all three trials. Between trials one and three 40.9% of participants maintained the same gait, 45.5% between three and five and 50.0% between trials one and five. This suggests that ladder climbing is a skill which takes practice to establish an individual’s preferential technique. This is largely relevant to research as it highlights the needs to include familiarisation sessions within ladder climbing studies to minimise the changes in technique during data collection sessions. These results are at odds with those of Dewar (1977) and opened the discussion of the most natural ladder climbing gait for individuals. However, understanding the true differences for technique preference would require statistical analysis such as an ANOVA which was not undertaken in this study. This work shows that prior to data collection on physiological or biomechanical variables that multiple familiarisation climbing bouts should take due to the variability in technique choice.

In 1988 Häkkinen, Pesonen and Rajamäki (1988) aimed to understand the causes of ladder climbing accidents due to their increasing prevalence in the workplace. Participants climbed a 70° ladder five times to ascertain different climbing habits and ten times at angles between 65 and 75°. The aluminium ladder was 3.5 m long with rung spacing of 30 cm and 40 cm wide rungs. Häkkinen, Pesonen and Rajamäki (1988) produced results which confirmed those of McIntyre (1983) i.e. that the largest two vertical forces were seen when a foot departed, i.e. maximal dorsiflexion and when it makes first contact with the ladder. A limitation of Häkkinen, Pesonen and Rajamäki’s study was the lack of raw results being reported, as shown in their figure 5 (Häkkinen, Pesonen and Rajamäki 1988). This makes it difficult to generalise the conclusions drawn from the first part of the article. Häkkinen, Pesonen and Rajamäki (1988) conclude that the smaller the pitch the greater the dynamic forces become and the steeper the pitch the more these dynamic forces decrease, which might reduce the risk of ladder slipping. However, this is at odds to the work of Dewar (1977) suggesting that the steeper the pitch the less balanced participants felt when climbing. This would indicate that there must be a compromise between exertion and scientific recommendation when putting forward an optimal ladder pitch angle which would impact on ladder design. Häkkinen, Pesonen and Rajamäki (1988) also noted that foot over foot style increased the lateral forces, although no data were shown to support this claim. Although this study consolidated the previous research conducted by McIntyre (1983), the lack of reported data makes it difficult to generalise the conclusions of this study.

Bloswick and Chaffin (1990) investigated the effect of different ladder climbing conditions on a biomechanical model and measured muscle activation using electromyography (EMG). They correlated hand forces with ladder pitch and found that as ladder slant increased, the forces on the hand decreased ($r = -0.69$) however, only 48% of the hand force is explained by ladder pitch ($r^2 = 0.48$, $p < 0.001$). They found that mean peak hand force from vertical ladder climbing was approximately 30% of body mass however, the raw data itself were not reported. These values are comparable to that of Armstrong et al. (2009) who reported 34-36% of body mass as the mean peak total hand force when climbing a vertical ladder. Bloswick and Chaffin (1990) also investigated the effect of 75° and 70° pitch on EMG activity. Bloswick and Chaffin (1990) clearly portrayed the change in total hand force using a graph to show that as ladder pitch increased the hand forces decreased 26% to 15% when the ladder was changed from vertical and pitched to 75°. This suggests that by moving a ladder from vertical it can decrease the reliance on upper body muscles and the task may have different muscular demands. However, any form of physiological demands at vertical or the difference between vertical and pitched had not been explored at this point.

Hammer and Schmalz (1992) followed on from the work of Dewar (1977) and McIntyre (1983) by analysing the techniques used when ladder climbing at 10° intervals from 50° to 90°. They recorded the techniques into four distinct categories: two-beat lateral gait, two beat diagonal gait, four beat lateral gait and four beat diagonal gait. The rankings of most common technique over all inclination were: two beat lateral gait, diagonal two beat, lateral four beat and then diagonal four beat gait. Although no clear data were presented to show the number of times each technique was recorded. However, these results are similar to those of McIntyre (1983) who also found lateral gait to be the most common technique used. However, there was also a high percentage of lateral four beat observed which was ranked third by Hammer and Schmalz (1992). The difference may be due to the inclination of the ladder which might affect climbing style preference and the method of analysis. Hammer and Schmalz (1992) analysed the global data set (n= 28 with 550 ascents) utilising all the climbs whereas McIntyre (1983) only had participants climbing at 75.5°. Previous work has highlighted the impact that altering the pitch of a ladder affects the hand and foot forces (Häkkinen, Pesonen and Rajamäki 1988; Bloswick and Chaffin 1990). Further to biomechanical impacts there were changes in the proportion of gait choices according to the differing ladder pitches (Hammer and Schmalz 1992). An example of this is that at 70° the second highest proportion of time spent climbing is the lateral four beat gait whereas at 50° diagonal two beat is much higher. The work by Hammer and Schmalz (1992) provides a more robust and complete view of the climbing techniques used by individuals across a variety of inclinations. This was the first study to examine climbing techniques involved in vertical ladder climbing. Vertical ascent showed a preference towards two beat techniques with approximately 75% of the bouts participants used the lateral gait which was, in general, the most used technique across all inclinations although the share decreased with inclination. However, this also leads to questions around how reproducible this is across numerous days. Furthermore, would this reproducibility change with experience or different speeds. Whilst these previously mentioned articles highlight trends in ladder climbing technique, neither specifically conducted any statistical analysis to compare the difference between the percentage time or observations of climbing techniques. However, the size of the data set and two articles reporting similar results suggest that lateral gait is the preferential technique for ladder climbing and that this becomes more prevalent as ladder inclination increases.

Up until 1992 the research focus has generally been on the comparison and understanding of the techniques of ladder climbing, rather than the demands of ladder climbing. However, this research whilst it is the best available it lacks the necessary focus to relate directly to the wind energy industry. For example. most research has been conducted on pitched ladders and not vertical ladders and the lack of robust physiology related papers makes it difficult to ascertain the demands of ladder climbing. At this mid point in the chronological timeline development of literature there has been a clear enhancement of knowledge however, many questions arose from the research. It was not for almost another 20 years before further research on ladder climbing was conducted and again a theme of research was followed.

2.5 Post 2000 Research

Vi (2008) conducted a study investigating the difference in energy expenditure and heart rate (HR) when repeatedly ascending and descending a 6.1 m height on both a vertical ladder and a ladder pitched at 75°. The use of a ladder of this length was longer than any previously conducted research. Participants were required to climb for at least 5 minutes at a rate which elicited a HR response of either greater than 90 beats per minute or 60% of age-predicted HR max, whichever was lower. Climb rate, recovery interval, total climbing time and test order were not reported, but there was a significant difference ($p < 0.05$) between both energy expenditure (11.4 kcal/min v. 13.1 kcal/min) and mean HR (142 bpm v. 155 bpm) when climbing at 75° and 90° respectively. Although the study by Vi (2008) highlighted that climbing at 90° has a larger energetic demand compared to that at 75°, it is unclear as to whether the climbing speed was consistent throughout and how the data were analysed. The use of short ladders with alternating climbing and descent involves a variable energy demand in contrast to prolonged ascending on longer ladders, potentially limiting the generalisability of the study to the longer ascents required for wind turbine towers. This was the first study to consider specifically the physiological demands of ladder climbing, however the duration, lack of analysis and the repeated ascending and descending nature of the task reduce its generalisability.

Subsequently there was a resurgence in interest in safety, with a focus on ladder climbing accidents and slips. Four published articles analysed accidents and sought understanding of the reasons behind slips (Armstrong et al. 2009; Lopez et al. 2011; Pliner et al. 2014; Schoenberg, Campbell-Kyureghyan & Beschorner 2015). Whilst informative, this research was not directly applicable to the fitness parameters relevant for wind tower turbine ascents because it was all conducted on short ladders. Nevertheless, it contributed to the understanding of slipping and accidents however, it does not help build a knowledge base which can aid in building a fitness standard for the wind energy industry. Milligan (2013) aimed to ascertain the demands of ascending and descending a 3 m ladder at different rates in order to aid in the creation of a fitness standard for oil and gas industry and the Royal National Lifeboat Institution (RNLI). Participants were required to climb continuously for three minutes both ascending and descending at 3 m ladder at three different climbing speeds. In doing so she recognised that the effect of continual ascending and descending of a ladder would alter the reported demand of ladder climbing by a reduction in the mean $\dot{V}O_2$ and HR. This is because descending a ladder is presumed to have a lower energy cost than that of descending, as was seen during pitched ladder ergometer climbing (Kamon 1970). Such a finding again highlights the need for specificity when conducting research when aiming to use it as a basis for a physical employment standard.

Despite a burgeoning wind energy industry which involves turbine ascents, our limited knowledge base of demands of ladder climbing is dated, incomplete and involving studies with low numbers of participants which pre-dated the wind energy industry. While such research appears to be the best there is available, it is not what is required to answer the relevant questions for the wind energy industry today. Prior to defining a fitness standard or PES within any industry, it is necessary to undertake a task analysis to understand the demands of the unique activity required of employees. Whilst current understanding of ladder climbing is based on the biomechanics of climbing and the risks of slipping. However, as yet there is not an understanding of the wind energy industry itself in order to base research on. Furthermore, the demands of vertical ladder climbing on long ladders is currently not known and this research is required to provide an evidence base from which a PES to be developed. Therefore, the purpose of this body of research is to gain a greater understanding of the wind energy industry and its practises whilst also aiming to investigate the demands of ladder climbing both pitched and vertical.

3.0 A Survey of wind turbine technicians

3.1 Introduction

It could be argued that there is less public knowledge of the role of a wind turbine technician than other more established roles such as those in the fire and rescue service and military. Currently there is a limited research base from which to develop an understanding of the industry making description of the role, or any part thereof, of a wind turbine technician difficult. The main sources of such information are personal communication, job advertisements or training documents (Appendix I) (Kudos Recruitment 2017a; Kudos Recruitment 2017b; Indeed.co.uk 2017; Renewable UK 2014). The lack of published research may in part be due to the relatively young nature of the industry with the first wind farm in the UK opening in 1991, 12 years after the formation of the leading industry body (Nixon 2008; Renewable UK 2018). It is plausible that the industry was overlooked for human factors research purposes due to larger and, what may have appeared to be more physically demanding industries requiring more immediate attention as well as the practical limitations of conducting research in the wind energy industry. In the wind energy industry there has been a lack of research within human factors but not in technical capabilities or engineering areas. Research in these areas is plentiful with groups such as Offshore Renewable Energy Catapult or companies such as Vattenfall innovating in new wind farms which continually seek development. There are several practical limitations of conducting research relating to human factors which could have impact on the undertaking of research. These practical limitations may include access to turbines themselves, required health and safety qualifications and cost implication from lost revenue due to conducting the research. These limitations may partly explain the lack of extant research which makes designing future relevant and generalisable research more challenging.

The previously mentioned challenges have led to a lack of literature that could be applied to the wind energy industry. Therefore, if a lack of research exists this makes it difficult to understand the basis for a physical employment standard (PES). PES currently exists for the wind energy industry within the UK (Renewable UK 2013) but a lack of research relating to the wind energy industry exists this makes the PES less robust. The development of such standards should be based around robust academic research and in conjunction with the industry. Recent work by Peterson et al. (2016), which built on the previous work by Tipton, Milligan & Reilly (2013), recognised the need for the research team to be involved early in the development of a fitness standard and familiarised with the types of tasks and duties of a wind turbine technician's role. The familiarisation of the research team should be undertaken before conducting a preliminary role review and analysis. A role review and analysis is key for understanding not only the main tasks which are undertaken in a role but also the nuances of these roles for instance time constraints, sequencing of combined tasks or factors which may positively or negatively impact performance. This is because whilst the key tasks may be outlined in documentation it is the details of such tasks which are necessary for understanding the broader role and designing relevant research appropriately. In the case of wind energy technicians this would be essential due to the lack of literature on the industry making it challenging to understand the key details regarding what day-to-day duties might involve. However, an approach such as that outlined by Peterson et al. (2016) requires buy-in from the industry bodies and companies, which can be difficult to gain. Therefore, without such engagement from an industry body an alternative method of acquiring such insight must be taken.

A starting point for gleaning such information is Renewable UKs health and safety training document (2014) which provides guidance on the training needs and framework for working on large wind turbines. This document (2014) suggests that the role of a wind turbine technician involves working at height and in confined spaces as well as requiring lifting and manual handling. The documentation acknowledges medical fitness as part of health and safety training as well as working at height, but it does not specifically outline the requirement to physically climb a wind turbine. These topics are suggested areas for training, but the document does not contain a needs analysis from which to base this on. While it does provide some idea of the tasks which technicians undertake, there are no specific details of these. This is because this is a training document to provide a standard to work towards rather than describing the requirement for the training. For example, it could state that working at height is required due to the requirement to undertake tasks at height up to 80 m above ground level. A more detailed training document was published by the Global Wind Organisation (GWO) (2014) which sub-divides its basic training course into three main modules: electrics, hydraulics and mechanics. This provides a detailed syllabus of the basic maintenance of these three sections; however, it fails to outline how often work in these areas takes place, perhaps due to company to company variation, and lacks specific details relating it directly to completing the tasks within a turbine.

Renewables UK’s (2013) medical fitness to work documentation highlights a number of key areas that may challenge employees within the industry which could potentially be classed as key demanding tasks. They identify ladder climbing, rescues, working in confined space, working in extreme ambient temperatures and transfers from sea to offshore turbines as potentially challenging areas. Whilst this provides an overview of some generic challenges of working within the industry, it fails to outline any key details of task requirements necessary for research teams to design robust research which could contribute to the academic literature. Aside from personal communication and the industry body guidelines there is a dearth of research which elucidates the exact requirements of the industry as a whole. As a result, research is urgently required in order to gain an understanding of expectations and current practice in the industry.

Therefore, the aim of this study was to gain an understanding of current practice within the wind energy industry. A secondary aim was then to garner information which can be used to design future vocationally relevant research.

3.2 Method

3.2.1 Study Design

The study employed a cross sectional design using an online survey hosted by SurveyMonkey (SurveyMonkey™ 2018). Survey monkey was used as a host platform instead of postal surveys due to requirement to post surveys to a gatekeeper to circulate, the cost implications of using postal surveys and the faster response time of online surveys compared to postal surveys (Shannon & Bradshaw 2002; Shih & Fan 2009). Although postal surveys have a higher response rate compared to electronic surveys the nature of this study meant electronic surveys were more practical as it did not require the sharing of employee details with the research team (Shih & Fan 2009). Furthermore, the use of an internet has been shown to yield more accurate results compared to an intercom, like telephone interviews (Chang and Krosnick 2009). These findings were like that of Bowling (2005) who found that participants would be more willing to confide sensitive information on self-administered electronic surveys compared to telephone surveys. Whilst the self-administered electronic survey ranked higher to the preference in mode of administration compared to telephone interviews (Bowling 2005). Face-to-face interviews were not used due to practical reasons and they have also been associated with Increased “yes saying”, reduced confiding of sensitive information, and high interview bias (Bowling, 2005).

Content validity was ensured through the use of two industry experts and the supervisory team to assess and advise whether the questions were relevant, met the aims of the study and covered all facets of a wind turbine technician’s role. Based on the literature a number of aims and questions arose which required answering in order to familiarise the researcher with the industry and fill in the gaps left by the sparse literature base. The process for the development of the survey is shown in figure 3.1. Based on the published literature and industry documentation an initial set of questions were drawn up (Renewable UK 2013; Renewable UK 2014). The themes the questions focussed on focussed on the role requirements of a wind turbine technicians such as: how often they climb turbines, what height of turbines they climb, the types of tasks completed and other extraneous factors affecting the role. These questions then received feedback from the supervisory team and the survey questions were adjusted accordingly. A telephone conversation was then conducted with two members of industry to garner further information from which to further develop the survey. These were management level individuals related to health and safety. A paper survey was then developed in conjunction with the supervisory team and piloted by the same two industry experts. The feedback from this was incorporated before the creation of a final survey (Appendix II). The study was then granted ethical approval by the School of Health Sciences research review group at Robert Gordon University, Aberdeen (SHS/15/22).

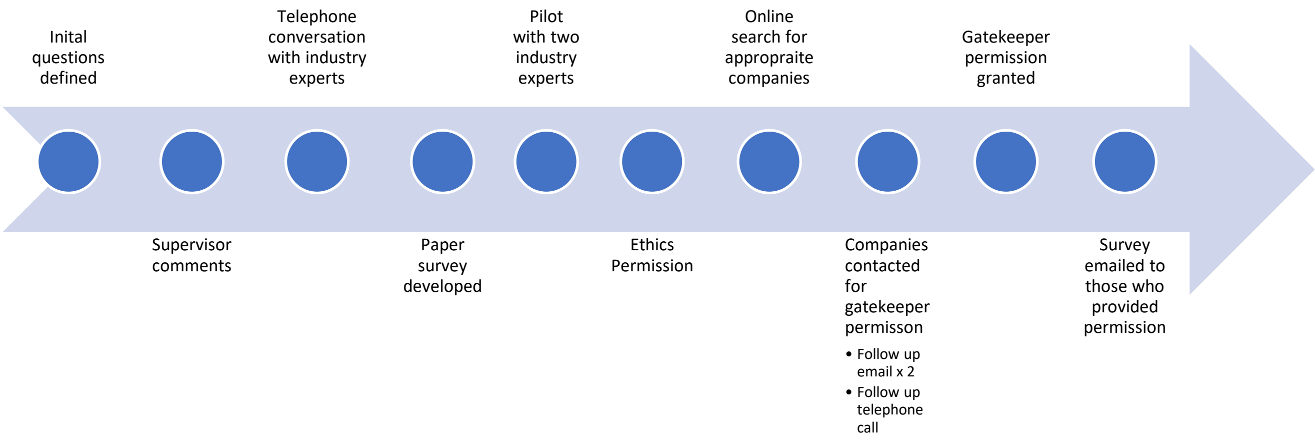

Figure 3.1 Wind turbine technician survey construction timeline

<u>3.2.2 Circulation</u>

3.2.2.1 Population and Sample

The population was wind turbine technicians/engineers from renewable energy companies who work on maintaining and servicing wind turbines. To be included in the study individuals had to be wind turbine technicians or engineers. Exclusion criteria was those who work on the construction of wind turbines, as the study aimed to understand the job demands of those servicing wind turbines.

3.2.2.2 Recruitment Method

Companies were contacted based on internet searches for industry contacts who service wind turbines and Renewables UK's database. Approaches were made to ask whether they would be interested in participating and for permission for them to circulate the survey to their service technicians; a total of over 40 companies were contacted. A follow up email was sent approximately one week after initial contact, and a further week later a telephone call was made; this was to help increase the potential response rate (Nulty 2008).

3.2.2.3 Data Collection Method

Upon receiving gatekeeper approval an email to the company outlining the purpose of the study and containing the survey monkey link to the survey and contact details for the researcher were sent. This was deemed more practical than sending postal surveys to the gatekeeper for them to circulate as it reduced costs and allowed for immediate forwarding. A copy of this email was then forwarded by the company to the relevant members of staff. In total four companies provided gatekeeper approval for circulation of the online survey. These companies covered areas including wind turbine servicing, training services, blade refurbishment and wind turbine development.

3.2.3 Data processing

Questions of a yes or no nature were analysed using a count and the difference assessed using a percentage. When questions required either multiple responses, numeric response or ratings the modal response was calculated. Counts were also made for each answer to allow for comparison between responses. For those answers where numerical input was required these were ordered and the mode taken. Questions requiring text and explanations had the responses presented as examples.

3.2.4 Statistical analysis

All statistical analyses were conducted in Microsoft Excel (Microsoft, Redmond, USA). Any participant who commenced the study was eligible to have their data analysed, this was to ensure that the maximum amount of data was captured and that if participants did not complete the survey their data was eligible to be used.

3.3 Results

3.3.1 Participant demographics

Fifteen participants commenced the study. However, one participant's data was excluded due to the turbine height being reported as 300 m tall. This was presumed to be the height of a mast rather than a turbine. The remaining fourteen participants' responses are presented within the results. Eight participants completed the entire survey. Of these, seven were male and one was female. Those who completed the survey had a mean (±SD) age of 41.3 (± 13.1) years with a mean self-reported stature and mass of 175.1 (± 9.7) cm and 81.9 (± 17.2) kg respectively. The length of time that participants (n = 15) had worked in the wind energy industry is shown in figure 3.2. The length of time that those who reported to employed in the industry greater than five years ranged from six to fifteen years.

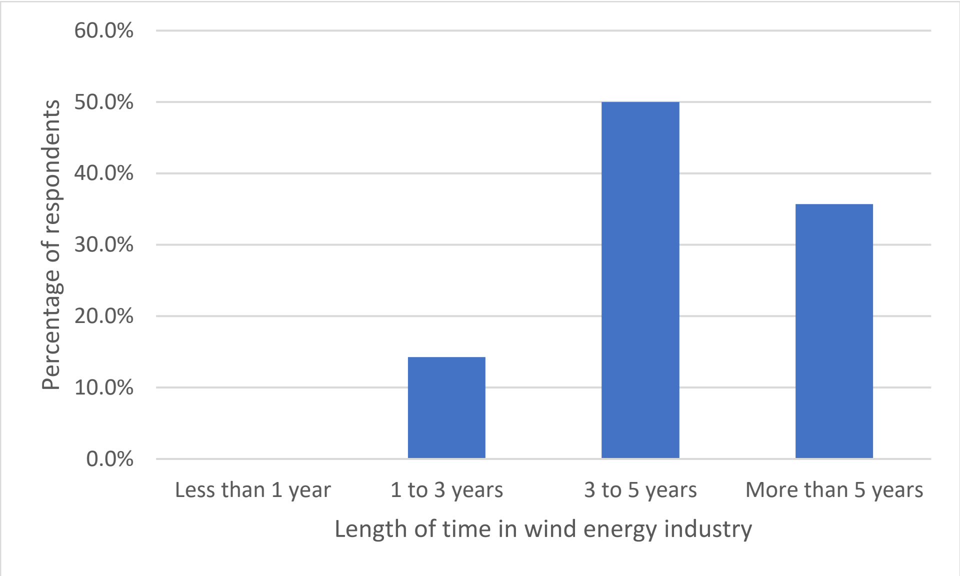

Figure 3.2. Length of time employed in the wind energy industry

<u>3.3.2 Wind Turbine Climbing</u>

The most common turbine size reported to be worked on was 36 m with heights ranging from 24 m to 82 m. The specific heights reported were 24 m, 36 m, 60 m, 75 m, 80 m and 82 m. The number of days per week on average that participants climbed wind turbines is shown in figure 3.3.

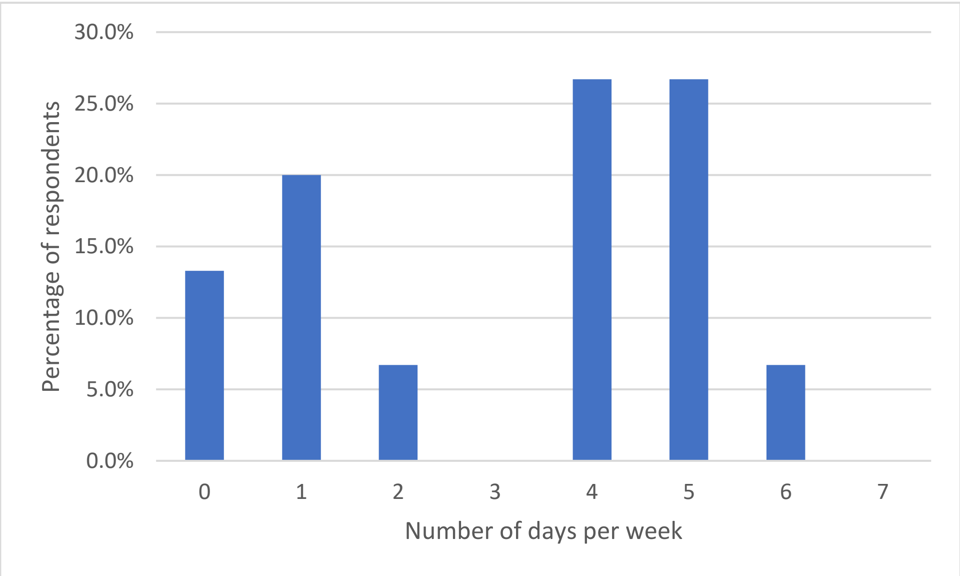

Figure 3.3 Number of days per week a wind turbine is climbed

On average 35.7% of respondents stated they climbed for between 16-30 minutes, whilst 21.5% climbed for 31-60 minutes with 14.2% climbing for less than 15 minutes. One individual stated that when they climb it is for a duration exceeding one hour. The mean typical daily height climbed was 43.1 m with responses ranging from 0 m to 100 m. The maximum height climbed in a day by participants was a mean of 55.4 m with responses ranging from 0 m to 150 m. The data from participants who said they do not climb turbines were included as they may not be required to climb turbines in order to service them or they do not regularly climb at least once per week on average.

When climbing a ladder 55.6% of the sample used a climbing bag with Petzl and Ridgegear the two brands used. Of those who used a climbing bag the stated loads were 1 kg, 5 kg and 15 kg. Participants reported that they rarely (37.5%) or sometimes (37.5%) found their posture being affected by the wind turbine when climbing. One participant reported that there are small access hatches within turbines which can be awkward to negotiate. The majority (71.4%) of participants said this was not further affected by personal protective equipment (PPE). Although one participant stated “helmet can get in the way, hanging straps can snag on protrusions when climbing or manoeuvring inside the nacelle”. It was reported by 62.5% of participants that the ladder width and/or rung spacing did not differ between turbines. Of those who responded to differences between ladders one participant stated that “some are wider and easier to climb”. Within this sample 25% of respondents had lifts in the turbines they worked on, whilst 37.5% of participants said the turbines they serviced had climb assist and 12.5% said turbines sometimes had climb assist.

3.3.3 Types of tasks completed

The responses to the types of tasks completed are shown in figure 3.4 with participants selecting all that applied to them. The other responses were servicing and being a second climber for safety reasons.

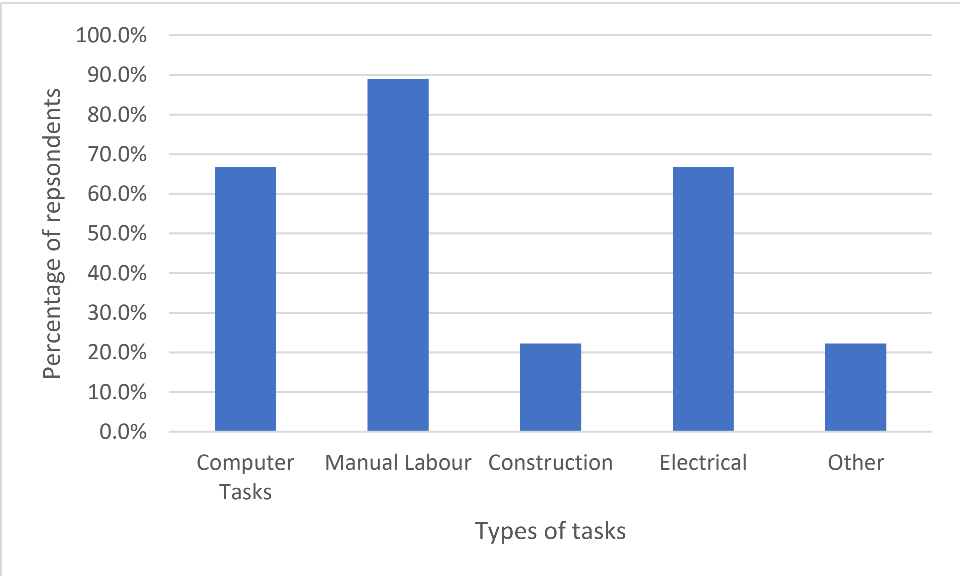

Figure 3.4 Response to types of tasks completed on a wind turbine

Further to this 66.7% of participants responded that the tasks have different demands depending on whether they are completed on the ground or within a wind turbine. Four participants stated that tasks completed differ due to space constraints with phrases such as “less space”, “very tight space/awkward access” or “small area to work in very confined”. Furthermore, the temperature might be colder, the light can be poor if late in the day and one individual reported that tasks differ due to fatigue from ladder climbing. Another factor reported was not having the required tool/equipment to hand at the top of the turbine. Once climbing has been completed 50% of the participants said they required a rest before completing a task, with durations of 2 and 5 minutes being reported as examples.

3.3.4 Confined space working

All respondents felt they either sometimes (62.5%) or often (37.5%) worked in a restricted space with details such as access point, nacelle size, hubs and cleaning under the generator being examples of restrictions. Due to the nature of the wind turbine 85.6% of the participants found their tasks difficult to perform. Further details provided information such as: “awkward due to access constraints”, “adverse weather conditions due to exposed locations”, “restriction in space”, “small work place many hazards trips slips etc and work at height”, “hub inspection on N60” and “brake caliper replacement”.

3.3.5 Other

Most participants (87.5%) when asked suggested that there was no aspect of their day-to-day job which could be investigated or improved upon. However, one participant suggested lifts or climb assist systems would improve their day-to-day job. Cold ambient temperatures mostly commonly (37.5%) “rarely” or “sometimes” affected participants when ladder climbing (Figure 3.5).

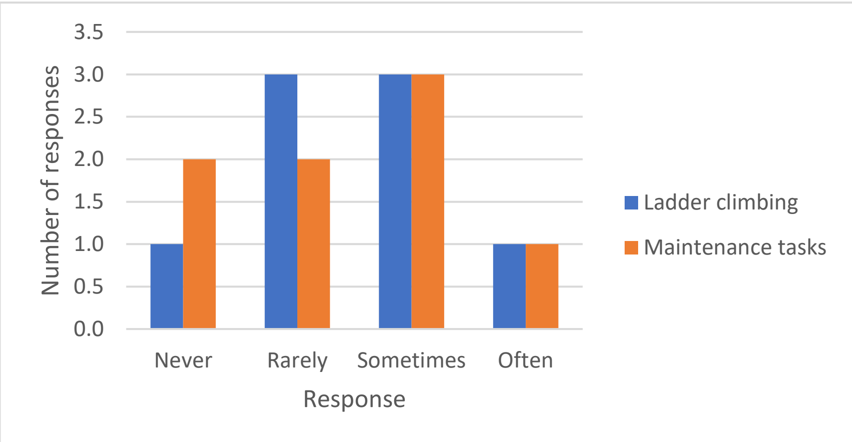

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Figure 3.5. Effect of cold ambient conditions on ladder climbing and maintenance tasks

It was suggested that this makes the ladder cold and slippery to touch, can cause cramping, cold hands can occur even with gloves on and it can make the air cold for breathing. ‘Sometimes’ was the most common answer (37.5%) when asked whether the cold affects the ability to complete maintenance tasks (Figure 3.5). Participants’ more detailed responses were that cold ambient conditions can cause cramp in the hands even with gloves on, and also numbness in fingers and hands. This can affect participants when tightening bolts or changing oil. It can also cause floors to freeze which can be difficult to clean. When asked whether hot ambient conditions affected them, 37.5% of respondents said ‘sometimes’, 25% responded for ‘never’ or ‘rarely’ with 12.5% choosing ‘often’. Further comments were hot ambient conditions can be very sweaty; can cause dehydration; dehydration and excess body heat can lead to dizziness. Fifty percent of respondents said that the hot ambient conditions never affect their ability to complete tasks, although 25% said ‘rarely’ with 12.5% selecting ‘sometimes’ or ‘often’. Further details were that when it is warm the nacelle lid can be opened to reduce the ambient heat.

Fifty percent of the sample had undertaken the Rescue 3 wind turbine safety operator course, with 37.5% having undertaken safe working at height course whilst one participant said they had no training on ladder climbing. The majority of participants (62.5%) did not have to undertake any form of fitness test before being given clearance to work on a wind turbine. However, of those who did (37.5%) they said they had either a step test, fitness exam or a medical and fitness test. Further to this 75% of respondents said fitness training was not provided before being given clearance to work although those who did get fitness training said the training was “medical”. In terms of advice, 87.5% of respondents said no advice was given to them on fitness, and of those who did receive advice it was given to them by a nurse. Within this sample 75% of respondents said they perform regular exercise outside of their daily living and occupational tasks. The details provided suggested this took the form of walking, cycling, running, gym work and general electrical work.

3.4 Discussion

The results highlight that a range of factors need to be considered when investigating ladder climbing such as frequency and duration of climbing, turbine height, load carriage, presence or absence of lifts and/or climb assist, space constraints and ambient temperature all having an influence. Further to this the results demonstrated that not all respondents undertook a fitness test and potentially there was variability in the process when one did take place. Only one participant stated that they undertook a step test whilst others defined these as “fitness exam” or “medical and fitness exam”. It is possible that these three processes could be the same or all three could differ. At the time of investigation, the Renewable UK fitness guidelines suggested that individuals were required to be able to climb the height of a turbine in the event of a lift failure or where no lift is installed (Renewable UK 2014). However, personal communication from those within the industry suggested that most modern wind turbines (post 2009) had lifts and that those in the industry were not required to regularly climb. This opinion differs to the results of this study which found that 60.1% of the sample climbed a turbine on either 4, 5 or 6 days per week whilst only 13% of individuals did not climb a turbine at all during a week. These results are similar to that of Garrido et al. (2018) who reported that 60.8% of respondents (n = 254) to their survey were always or often faced with ladder climbing when working on off shore wind turbines. When solely focussing on technicians this value grew to 76% with turbine heights reaching up to 115 m. Caution should be taking when cross-comparing this present study with the work of Garrido et al. (2018) due to Garrido et al. (2018) solely focussing on off shore wind. A possible reason for the results found in this study not reflecting the opinion provided when piloting the questionnaire was that the industry experts who undertook the pilot both worked on larger turbines with lifts. Whereas those sampled typically worked on smaller turbines (mode- 36 m) which are far less likely to have them. This difference between the personal communication and those who completed this survey could highlight a non-response bias in this study or it could be that those who the survey was piloted with were not typical of the workforce. Sax, Gilmartin and Bryant (2003) suggested that low response rates, as in this study, need not necessarily mean that non-response bias occurs unless the non-responders' responses would differ from those who responded. A non-response bias could have taken place for two main reasons: company size and double subcontracting. No large companies provided gatekeeper approval to circulate this survey or other companies double subcontract the servicing of turbines making it difficult to access the relevant individuals. More recently changes were imposed which prevented the use of lifts in turbines due to the incidents occurring in mainland Europe (Vorhölter 2015; Personal correspondence) such as in 2015 after incidents which led to a manufacturer releasing a safety alert stating not to use specific service lifts (Global Wind Safety, 2017). Therefore, this suggests that due to the inability to use the lift the number of vertical meters required to be is climbed is likely to increase as individuals will still have to maintain the planned maintenance schedules. Depending on turbine size the workforce could potentially spend in excess of 30 minutes climbing for an 80 m tower. This is based on individuals reporting the most common climbing time as 15-30 minutes as the modal climbing time with a modal turbine height of 36 m. The lack of evidence surrounding the fitness required of wind technicians, together with the likelihood that a sudden increase in climbing workload would be a risk factor for injury, this underscores the vulnerability of the industry in having to respond to any enforcement order by the regulating authority. Therefore, there should be research targeting improving the depth of knowledge on ladder climbing specifically related to this industry.

Research which has focused on fitness standards suggest that they should aim to encompass all or most of the activities which take place in a specific role (Petersen et al 2016). Renewable UK's (2014) medical fitness guidelines state that it is necessary to be able to climb a wind turbine. However, it was not mentioned as to the precise circumstances surrounding this, for example whether this is to be done with a load or with/without assistance and whether there is a time limit. Whereas work schedules and daylight availability may still be able to have an influence with onshore wind turbines. Furthermore, if considering off shore wind turbines weather, sea state and tides all may exert time and psychological pressure for offshore renewable servicing (Mette et al. 2017). Data from the current study showed that when an external load is carried that it ranges from 5 kg to 15 kg, which has not previously been definitively reported in the literature. Garrido et al. (2018) highlight that technicians often have to move heavy loads whilst climbing as well as wearing survival suits. It has been outlined that the role of wind turbine technician in off shore wind turbines in Germany is physically demanding and "skipping up a ladder in a survival suit is certainly not everyone's cup of tea" (Mette et al. 2017). Investigations defining the effect of load carriage have taken place in other industries and tasks such as walking, firefighting and the military, although not related to vertical ladder climbing (Kamon, Metz and Pandolf 1973; Phillips et al. 2014; Taylor, Peoples and Petersen 2016). An understanding of the effect of load carriage is crucial as if this is a necessary load then the demands must be understood in order to recruit those deemed fit enough to undertake the relevant roles. However, it must be understood whether such loads are necessary and how they affect task performance as the recruitment of capable and injury resistant individuals must be balance against inappropriate discrimination (Taylor, Peoples and Petersen 2016). This complex process which requires understanding the appropriate work rate, an understanding of PPE as well as appropriately training individuals to ascertain the demands of external load carriage and ladder climbing (Taylor, Peoples and Petersen 2016). Nevertheless, this highlights a crucial area where future research should occur. Further to this it was identified by individuals that they do not use climb assist devices and that one individual mentioned it is something they felt would improve the ability to fulfil day to day job requirements. Like loaded climbing there is a paucity of research relating to the use of climb assist devices within any industry. Therefore, research that investigates and begins to understand the effect of these factors would be of interest to both the scientific community and the industry. Without such evidence, it is difficult for individuals and companies to make informed decisions about the equipment. They must solely base their decision on manufacturers claims without understanding the effect of it. Both these factors could potentially have an impact on ladder climbing, by substantially increasing or decreasing the physical demand involved.

The tasks identified by the respondents reflected those outlined by the industry body Renewable UK and the training providers. The majority of participants (88.9%) identified manual labour tasks, electrical and computer tasks (both 66.8%) with two thirds of those stating that the tasks differed from when completed on the ground because of the reduced space inside the nacelle. These stated demands are reflected in the training standards (Renewable UK 2013; Renewable UK 2014) which mentioned that confined space is one of the areas for training whilst the medical fitness document defines that musculoskeletal flexibility is required for working in confined space (Renewable UK 2013). This was reinforced by the fact that more responses stated that “some tasks are awkward due to space constraints” and that the area is a “small work place”. These reports are similar to those reported by Mette et al. (2017) where individuals were working in awkward spaces. Furthermore, Garrido et al. (2018) reported 65% of participants often had the physical strain of restricted movement whilst 80% often worked either twisting forwards or sideways, indicating awkward spaces. Space constraint has been identified as a factor affecting those working in wind turbines both on and off shore; however, no current research has investigated this area in relation to wind energy to date.

The guidelines of Renewable UK (2013) suggest that fitness testing to assess the physical fitness to climb should take place for all employees with the suggestion being that either the Chester Step Test or a shuttle run test is undertaken. The results of this survey suggest that this is not being implemented as only 37.5% of individuals said they did undertake a fitness test with the Chester Step Test being the only recognisable test mentioned. It is thought that the other two respondents may have forgotten or not known the exact type of test undertaken with the responses being “fitness test” and “medical and fitness test”. This result suggests that the guidelines provided by Renewable UK (2013) are not being adhered to as not all individuals undertook a form of medical or fitness test. Therefore, this is putting individuals at risk as not all individuals who are climbing ladders are being deemed fit enough to climb. A greater understanding of how often fitness testing takes place would be of interest as these results suggest that it is not common place. In addition, the lack of fitness training provided before being given clearance to climb might be inappropriate because as outlined by Mette et al. (2017) and Garrido et al. (2018) the role of a wind turbine technician is physically demanding and challenging and technicians should be suitably prepared for the role. Only one participant responded saying he/she was given advice on fitness training before such clearance was granted and due to the challenging nature of the role it would be beneficial to provide advice to potentially aid employees. The provision of advice would be in line with the idea put forward by

Renewable UK (2013) that those who do not achieve the appropriate standard undergo appropriate fitness training and, where appropriate, dieting. Most of those who took part in the survey (75%) undertook activity although they did not state whether or not this was to reduce fatigue when ladder climbing. Those that did exercise said it was generally walking, cycling, running or going to the gym. This suggests that whilst the fitness activities may take place they are not engaged in by all individuals. It should also be recognised it is not known whether these are activities they may do for enjoyment or other reasons or whether they are to keep fit for their occupation. This is an unavoidable limitation of using cross-sectional survey design.

The aim of this survey was to provide a greater understanding of the role and expectations placed on wind turbine technicians and the nuances of the role. This survey identified that a number of different tasks take place in the industry, which reflects what was reported in industry documentation. However, it expands on this by highlighting that the tasks often take place in restricted space rather than an open environment and flags the interaction of climbing with subsequent working as a key future research area. It further identified that ladder climbing takes place to a greater extent than previously appreciated with the majority of respondents climbing a turbine at least once per week up to as many as six days per week. Ladder climbing has previously been identified as a physically demanding task (Kamon and Pandolf 1972). However, research is lacking for understanding the physiology of ladder climbing and the research by Kamon and Pandolf (1972) is not sufficient to base a fitness standard on. This is due to the lack of specificity with regards to the type of ladders involved as well as the external loads carried and the position of the loads. Petersen et al. (2016) suggest that research teams and experts should identify physically demanding tasks when creating a fitness standard for occupational groups. However, as has been previously mentioned the entire extant literature on ladder climbing is limited and thus insufficient to create such a standard from. This survey highlights that ladder climbing within the wind energy industry is a complex area with many dimensions to be considered when aiming to assess the demands of ladder climbing (Figure 3.6). Figure 3.6 shows there are many areas to consider which may alter the demands of ladder climbing such as climb assist, external load carriage and potentially space restriction. Whilst many of these other factors may exacerbate or alleviate the demands of ladder climbing, the ability to conduct research on such factors may be challenging. When identifying areas for future research there are many factors to be considered such as practicality, relevance and the ability to provide the evidence base sufficient to alter practice or legislation.

Figure 3.6 Factors relating to vertical ladder climbing in the wind energy industry

*Green – Survey based factors, Orange – Literature based factors, Blue – Anecdotal evidence factors

The figure below (Figure 3.7) highlights the ability or inability to currently investigate the different factors identified either in figure 3.6. There were a number of factors that could have been investigated (Green) with the potential impact relative to the thesis aim of understanding whether the current medical standard was fit for purpose. Furthermore, whilst some factors could have been investigated the initial implication of these factors (Forearm fatigue) was not seemingly clear until chapters seven and eight by which point the research program had been set. Thirdly, whilst certain topics would have been of great interest to increasing the literature base the results of the survey did not highlight the importance of these compared to the anecdotal evidence gained within the later chapters. The two topics highlighted in orange had potential to be investigated in conjunction with the industry but not in the laboratory setting. Those factors in the black at the time of writing were unable to investigated and were not considered for future investigation. The secondary aim of this study was to identify topics for future research and based on the outcome of the survey three topics were identified as important to be investigated: the effects of external load, climb assist, and restricted space on vertical ladder climbing. These areas are absent from the current knowledge base, could be practically be investigated, align to the aims of the thesis and could impact on industry practice. The inclusion of climb assist was made possible due to communications with an external company which allowed for the conducting of research at a training facility to investigate the effect of a climb assist device (Chapter six).

Figure 3.7 Potential research topics

*Black – Unable to investigate, Green- Able to investigate, Orange- Potential to investigate

3.5 Limitations

The main limitation within this study was the small size and as outlined in 3.2 over 40 companies were approached for gatekeeper approval but most did not respond. The limited contacts within the supervisory team were fully exploited, but despite this, reaching senior figures with decision-making and line management responsibilities proved problematic. There are several difficulties in accessing participants due to the double sub-contracting nature of the industry and often companies contracting out the servicing of turbines to other companies. Therefore, the generalisability of the findings was limited by the small sample size. The reason for this was either no response or no interest from the companies when they were approached for gatekeeper approval. Furthermore, the structure of the industry means some companies sub contract the servicing of the turbines and therefore they do not directly employ service technicians. This then made it difficult to attract respondents because targeted companies generally did not undertake the work themselves. As has been alluded to earlier in this chapter there were differing responses based on anecdotal evidence compared to the results of the survey. It is expected that a non-response bias occurred which could in part explain the differences in findings from the expected results (Sax, Gilmartin & Bryant 2003). Over 40 companies were approached and contacted on multiple occasions through email and telephone calls but they either failed to respond or refused to provide gatekeeper approval. This was most likely because of a lack of initial contact within the company, overall industry buy in and the double sub-contracting within larger companies. Whilst a larger sample size would have been desired, the study succeeded in gaining some understanding of what takes place in the industry and where the practical aspects of this research project should focus. The response rate to the survey was not known due to a lack of knowledge on the number of wind turbine technicians within each company who provided gatekeeper approval being unknown. Approximately 10% of the companies approached provided gatekeeper approval however, the number of individuals who met the inclusion criteria was not known. Understanding the response rate would have been beneficial to ascertain how many individuals responded but perhaps the focus in future should move towards improving both response rate and increasing the number of companies providing gatekeeper approval. A potential low response rate may mean than a sample bias may take place, however, a high response rate with few gatekeepers could also lead to this within a diverse industry.

3.6 Conclusion

The wind energy industry is a complex one that has many facets to be considered with its workforce having to deal with a range of different types of task as identified by this study (Figure 3.6) and Garrido et al. (2018). Current medical fitness demands state that employees should be able to climb 80 m however, no current estimated duration has been put forward until this research took place. Previously anecdotal evidence suggested that ladder climbing was rare amongst wind technicians, however this study and recent work by Garrido et al. (2018) highlighted it takes place on a regular basis. When ascertaining the demands of a task Petersen et al. (2016) highlighted that all aspects of a task should be considered. The implication from this study is that there is need to understand the nuances of ladder climbing and specifically the impact of external factors. This is because external load or climb assist, which could increase or decrease the demands placed on climbers which would impact a fitness standard. This thesis has previously outlined an aim to understand the demands of ladder climbing and in line with recommendations by Peterson et al. (2016) this chapter highlights the need for an increased focus on understanding factors that can affect ladder climbing. Therefore, as this thesis aims to understand whether the current medical fitness standard is appropriate and the demands of ladder climbing the initial chapters will be based around understanding the demands of unloaded ladder climbing. However, subsequent chapters will aim to elucidate the effect that external load, restricted space and climb assist have on the demand of ladder climbing (Figure 1.2). Therefore this study has commenced in elucidating the many factors to be considered with ladder climbing but acknowledges that a broader reach is required to fully understand the current practices within the renewable energy industry.

4.0 A reliability study of physiological and psychophysical variables in relation to pitched ladder ergometer climbing

4.1 Introduction

Reliability can be defined as the consistency of measures of individual performances on a test (Atkinson and Nevill 1998). Understanding reliability is important for a number of reasons such as assessing change between two values or quantifying learning effects and variation within a measure (Atkinson and Nevill 1998; Hopkins 2000). Atkinson and Nevill (1998) divided measurement error into two components: systematic bias and random error. Systematic bias can be a learning effect across multiple trials for example, but also the difference in measurement between two pieces of equipment conducting the same measurement. Random error could be from biological or equipment variation, such as the impact of different climbing techniques between testing sessions if technique is not defined. (Atkinson and Nevill 1998). The understanding of systematic error has implications for familiarisation of a task and could be used to dictate the number of familiarisation sessions required to minimise the systematic error.

Ladder climbing takes place in a number of industries, and as highlighted in the previous chapter is a critical task within the wind energy industry. This is because it is often faced by wind turbine technicians and would appear to be physically demanding due to the requirement of rest before commencing a task and the reported descriptions in the research of Mette et al. (2017). As has been previously reported research relating to ladder climbing, both pitched and vertical, is sparse and to date no research has been published on the reliability of ladder climbing. By deeming ladder climbing as a critical task then understanding the reliability of measures such as $\dot{V}O_2$, heart rate (HR) and rating of perceived exertion (RPE) relating to this task is important. The impact of this could lend itself for assessing the impact of interventions such as loaded climbing, climb assist or changes in techniques. This makes it imperative for research purposes to ascertain the reliability of physiological measures as this could provide a research base from which research could grow and understand any learning effect within ladder climbing.

Therefore, the aim of this study was to investigate the reliability of $\dot{V}O_2$, HR and rating of RPE during ladder ergometer climbing. Further to this, the secondary aim was to assess whether the reliability was affected by climbing speed.

4.2 Method

4.2.1 Study Design and Justification

The study was a repeated measures design with participants completing four sessions (one familiarisation and three measurement sessions) each comprised of three climbing bouts at three speeds, with order of the speeds randomised within the session. Randomisation was employed to minimise the potential of order affecting results. This aimed to reduce the effect of both fatigue and learning throughout the study. There was a minimum of 24 hours between each of the sessions (Figure 4.1). This study was approved by the School of Health Sciences ethics review group at the Robert Gordon University, Aberdeen (Study No: SHS/15/03). This study aimed to also contribute towards chapter five comparing pitched versus vertical ladder ergometer climbing and due to the inability to control for menstrual cycle and the unknown nature of the differences between the testing days for pitched and vertical climbing trials, only male participants were recruited. Although it has generally been seen not to affect aerobic performance (Constantini, Dubnov and Lebrun 2005) the effect is individualised and by only recruiting male participants it removed gender and menstrual cycle as potential confounding factors.

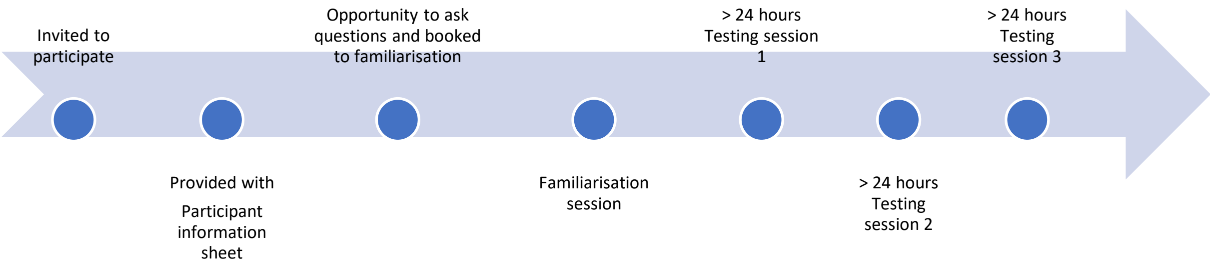

Figure 4.1 Study timeline

4.2.2 Participants

Twenty-five heathy male participants were recruited by word of mouth and emails to sport and exercise science students at the Robert Gordon University, Aberdeen. They were provided with a copy of the participant information sheet (Appendix III) and were given an opportunity to ask questions before agreeing to participate in the study. At this point all participants provided informed consent (Appendix IV) and completed a pre-activity readiness questionnaire (PARQ) (Appendix V). All participants were free to withdraw from the study at any point without providing a reason. Their mean demographics are shown in table 4.1.

Table 4.1 Physical and demographic data of participants (N = 25)

Age (years)	Stature (cm)	Mass (kg)
19.8 (± 2.1)	177.1 (± 5.5)	71.5 (± 7.7)

Values are mean and SD

4.2.3 Protocol Development

The protocol was based on work by Kamon (1970) which investigated ascending and descending a 60° ladder ergometer. The three speeds used in this study were modified based on the vertical climbing rates outlined by Kamon (1970) and converted to a 75° speed using equation 1 with a pictorial representation shown in Figure 4.2.

75° Speed = (Kamon 1970 Ascent rate) / (sin 75) [equation 1]

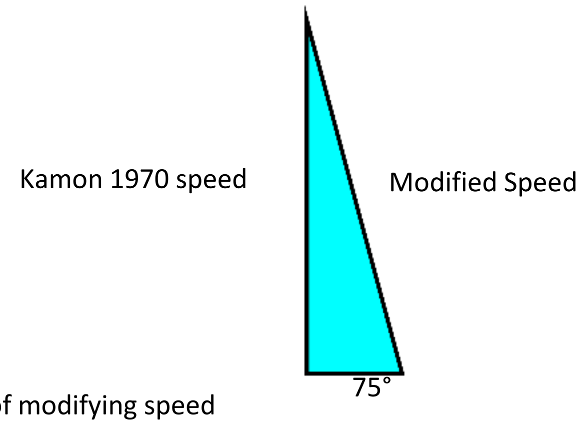

Figure 4.2. Example of modifying speed

The three vertical climbing rates which were clearly outlined by Kamon (1970 p.3) were 9.46, 12.36 and 14.85 m per minute. The equivalent derived speeds are shown in table 4.2.

Table 4.2 Original and modified ladder ergometer climbing speeds

Kamon speed	9.46	12.36	14.85
Modified Speed	9.8	12.8	15.4

Values are in m per minute

4.2.4 Experimental Protocol

4.2.4.1 Familiarisation session

On arrival participants were given another participant information sheet to read and the protocol explained to them. This was to ensure if they had any further questions they had were answered at this point they completed a PARQ and provided written informed consent. Prior to any ladder climbing participants were familiarised with the Borg CR-10 RPE scale (1980). Whilst the Borg 6-20 scale is generally suggested for the use of whole body exertion (Winter et al. 2007) the practical use of the CR-10 was preferred in this case due to the concentration and coordination required to ladder climb, the increased number of semantic anchoring terms (6 v 9) and less numbers allowed for individuals to take less time to provide RPE ratings compared to the 6 – 20 scale. Conceptually participants found the CR-10 scale more straightforward than the 6 – 20 scale. Although its strength lies in targeting body specific parts, it can also be used as a marker of perceived cardiorespiratory effort (Noble and Robertson 1996).

The participants then completed three climbing bouts of a 75° pitched ladder ergometer (Figure 4.3) (H/P Cosmos, Italy) at in ascending speed order of 9.8, 12.8 and 15.4 m per minute with a five-minute recovery between each stage. The ladder ergometer was slowly accelerated to the required speed and communication maintained with the participants to make sure they were comfortable with each speed. Participants were deemed technically competent at climbing if they could continuously complete 5 minutes of ladder ergometer climbing at each speed. The participants were then scheduled in for the three testing sessions which were a minimum of 24 hours apart (Figure 4.1). Although the work by Hammer and Schmalz (1992) suggested that ladder climbing technique was not consistent over five trials which suggests a learning effect took place undertaking more familiarisation trials were not deemed necessary. This was because the total duration of ladder climbing was most likely less than the duration in this familiarisation session (15 minutes) which allowed participants to adjust their techniques accordingly.

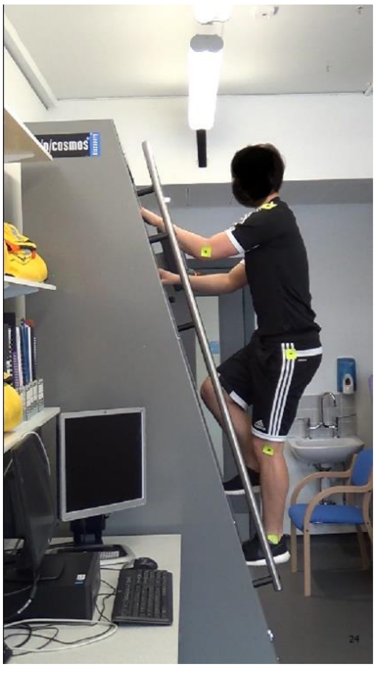

Figure 4.3. 75° Ladder Ergometer

4.2.4.2 Testing session

On arrival in the laboratory, the researcher established whether any changes had occurred from the completed PARQ and explained how the testing session would be conducted. Participants then had their stature and mass measured and recorded using a standard protocol (Stewart et al. 2011) prior to each testing session.

Participants were then fitted with a Polar T7 (Polar Fi, Kempele Finland) heart rate monitor strap before completing a five-minute warm up on the ladder ergometer climbing at 7 m per minute. Upon completion participants were then fitted with a pre – calibrated (see appendix VI) Cosmed K4B2 breath by breath gas analysis system (Cosmed, Rome, Italy) before being informed of the order of the speeds for that session. Participants then completed three five-minute bouts of climbing with a five minute recovery between bouts. RPE was recorded during the final 30 seconds of each bout. The average HR and $\dot{V}O_2$ values were determined by taking the mean value for the final minute of each bout of climbing. This protocol was then repeated twice more, with randomised orders, for the next two testing sessions which took place a minimum of 24 hours apart. These outcome measures were chosen as they had the capability to be measured within the laboratory setting and $\dot{V}O_2$ in later studies could be mapped against current medical fitness guidelines. Whilst the combination of HR and RPE as well could be used to aid in the assessment of how hard individual could be working towards maximum. Furthermore, RPE was used in order to assess understand whether the perception of effort calibrated against a change in $\dot{V}O_2$ for this and the following study (Chapter 5).

4.2.5 Statistical Analysis

All statistical analysis was conducted in either Microsoft Excel (Microsoft, Redmond, USA) or SPSS V21 (IBM, Armonk, USA). Mean values were calculated for HR, $\dot{V}O_2$ and RPE for each exercise bout within a session. A repeated measures ANOVA was run in order to assess for any changes between the tests within speeds (Weir 2005). Intraclass correlation coefficient (ICC) was used to assess the relative reliability of HR and $\dot{V}O_2$ using ICC 3,1 (Atkinson and Nevill 1998; Weir 2005; Hopkins 2011). This was due to aiming to ascertain the effect of random error rather that systematic error. No benchmark comparisons were used to compare ICC against as there are numerous ICC equations that make comparing against ratings difficult (Weir 2005). Furthermore, the variability within the dataset affects the magnitude of the ICC (Weir 2005). In order to assess absolute reliability the standard error of measurement (SEM) was also calculated (Weir 2005). These were the standard error of measurement (SEM), coefficient of variation (CV) and limits of agreement (LoA) (Atkinson and Nevill 1998). These equations can be seen below with SD, representing the SD of all participants within that condition, V representing the chosen variable, x representing the mean, and a and b represent the given testing sessions compared (either 1 v 2 or 2 v 3).

$$SEM = SD\sqrt{1 - ICC} \qquad \text{Equation 2}$$

$$CV = \frac{SD}{\bar{x}} * 100 \qquad \text{Equation 3}$$

$$Bias = \bar{x}(V_a - V_b) \qquad \text{Equation 4}$$

$$Random\ Error = 1.96\sqrt{2SEM} \qquad \text{Equation 5}$$

The random error component of the limits of agreement was calculated using the mean square error (MSE) from a repeated measures ANOVA within each variable (Equation 5). This method was used instead of the 1.96 multiplied by the SD of the differences between two testing values as this study conducted multiple retests instead of a standalone pairwise comparison. The upper and lower LoA were defined as the bias ± random error.

A two factor repeated measures ANOVA with a Bonferroni post hoc test was used to assess any differences between the trials and between speeds. A Bonferroni post hoc test was used to assess the main effects and reduce pairwise error (Field 2012). The two factors defined were the speed and the test session. Significance was set at $p < 0.05$. Pearson's correlation co-efficient was used to assess agreement between RPE at trials two and three in line with previous literature for assessing RPE agreement (Skinner et al. 1973).

4.3 Results

4.3.1 Reliability Results

All variables were normally distributed and a repeated measures one way ANOVA showed no significant difference within speed between trials for $\dot{V}O_2$ or HR. The reliability statistics for $\dot{V}O_2$ are shown below in table 4.3. The ICC, SEM, LoA cover all three trials within a single climbing speed whereas CV is only for each individual trial. Bias is shown for the mean difference between the previous trial. At the slowest and fastest speeds CV reduced in size with the final testing session showing the lowest values. This CV for the medium speed was lowest with the first testing session.

Table 4.3. $\dot{V}O_2$ reliability data

	Speed (m per minute)								
	9.8			12.8			15.4		
	T1	T2	T3	T1	T2	T3	T1	T2	T3
ICC		0.57			0.47			0.34	
CV (%)	8.37	7.62	6.60	6.43	7.18	7.07	7.47	6.55	6.29
SEM		1.60			1.94			2.43	
Bias		0.22	-0.13		0.18	0.27		1.29	-1.22
± LoA		4.69			5.48			6.43	

The reliability data for HR, shown in table 4.4. At the slowest and fastest speeds CV is higher at the first session and lowest at the final session showing smaller variation in the group. At the medium speed the CV is lowest in the first session before increasing in session two and reducing again at session three however, it is still higher than session 1 (11.23 bpm v 12.19 bpm). The bias for the speeds suggests there is a small deviation in HR response between sessions although this was not significant. The LoA is lowest at the fastest speed 16.7 bpm whilst the medium speed has the largest LoA (20.9 bpm). RPE showed highest agreement at the slowest speed (r = 0.81) with the medium speed (0.56) showing the lowest agreement and the fastest speed between session two and three was r = 0.72.

Table 4.4. HR reliability data

	Speed (m per minute)								
	9.8			12.8			15.4		
	T1	T2	T3	T1	T2	T3	T1	T2	T3
ICC		0.89			0.84			0.90	
CV (%)	12.47	12.28	12.19	11.23	12.63	12.19	10.10	10.58	9.66
SEM		5.8			7.2			5.2	
Bias		-0.8	0.4		-0.9	3.2		2.6	-1.7
± LoA		18.3			20.9			16.7	

4.3.2 Comparison of speed

The mean (± SD) HR and $\dot{V}O_2$ values for each stage and session are shown in table 4.5, below. There was a significant interaction between speed and session observed ($p < 0.05$). Further analysis showed that a significant interaction occurred between session 2 and 3 at the medium and fast speed. However, no significant differences in oxygen consumption were observed between sessions within speeds. Results showed a significant main effect for speed highlighting that as speed increases there is a significant increase in the oxygen consumption and HR ($p < 0.05$). Oxygen consumption increased by 19.6% and 11.7% from slow to medium and medium to fast speeds respectively.

The results for heart rate, shown in table 4.5, showed no interaction between session and speed but a significant main effect for speed was observed but not for session order. Pairwise analysis showed a significant increase in HR between the slow and fast speeds as well as the medium versus fast speed. These changes were a 9.2% and 6.2% increase in HR respectively.

Table 4.5. Mean $\dot{V}O_2$ and HR data

	Speed (m per minute)					
	9.8		12.8		15.4	
	$\dot{V}O_2$ (ml.kg.min^{-1})	HR (BPM)	$\dot{V}O_2$ (ml.kg.min^{-1})	HR (BPM)	$\dot{V}O_2$ (ml.kg.min^{-1})	HR (BPM)
Trial 1	32.73 (2.74)	142.3 (17.8)	39.2 (2.5)	156.2 (17.5)	44.17 (3.30)	166.7 (16.84)
Trial 2	32.51 (2.48)	143.1 (17.6)	39.05 (2.81)	157.1 (19.9)	42.89 (2.81)	164.1 (17.4)
Trial 3	32.64 (2.15)	142.7 (17.4)	38.78 (2.74)	154.0 (16.8)	44.1 (2.78)	165.8 (16.0)
Mean	32.63 (2.47)	142.7 (17.6)	39.02 (2.69)	155.8 (18.1)	43.7 (3.0)	165.5 (16.8)

All values are mean (±SD)

The results for RPE are shown in table 4.6 below with the median RPE values being reported. The trends show no change within the medium and fast speeds with median values of 3.0 and 4.0 being reported across all sessions. Whilst at the slowest speed the second trial had a median of 1.0 compared to trials 1 and 3 where the reported medians values are 2.0.

Table 4.6. Median RPE data

	Speed (m per minute)		
	9.8	12.8	15.4
Trial 1	2.0	3.0	4.0
Trial 2	1.0	3.0	4.0
Trial 3	2.0	3.0	4.0

4.4 Discussion

4.4.1 Reliability

The reliability data outline that at slow speeds relative and absolute reliability of $\dot{V}O_2$ is higher than when compared to the medium and fast speed. This was also represented in the RPE agreement with higher agreement at the slowest speed ($r = 0.81$), which opposes the work of Eston and Williams (1988) however, their lowest correlation was $r = 0.83$. The results in table 4.2 show that the SEM increases from 1.6 ml.kg.min^{-1} to 1.9 ml.kg.min^{-1} and then 2.4 ml.kg.min^{-1} respectively. However, SEM for HR response is consistent between the slow (5.2 bpm) and fastest speed (5.8 bpm) but not the medium speed which has an SEM of 7.2 bpm. There is not a discernible technical reason why the HR reliability data differs for the medium speed compared to the other two conditions. $\dot{V}O_2$ is in general considered the critical measure within physical employment standards and the implications of the results suggest that the speed could be critical in ascertaining the effect of any interventions. This is because as the SEM increases the smallest detectable change will also get larger therefore, if it is appropriate slower climbing speeds would allow for the collection of less variable data (Weir 2005).

The data also suggest that if any learning effect occurred that the effect on oxygen consumption was small as the with largest change from the first testing session to the last was 0.5 ml.kg.min^{-1}. This occurred in the medium speed where this was the only speed to show two consecutive rises in the mean $\dot{V}O_2$ values compared to the slow and fast speed which rose (0.22 ml.kg.min^{-1} and 1.29 ml.kg.min^{-1}) however, these both were lower again in trial three (-0.13 ml.kg.min^{-1} and -1.22 ml.kg.min^{-1}). Inclusive of a familiarisation session this suggests that a large learning effect does not occur within pitched ladder ergometer climbing. The work of Dewar (1977) found that over five trials only 31% of participants maintained the same technique which suggests that throughout this study individuals would have been likely to be altering their technique. This study did not ascertain whether participants were consistent within their technique however, any change in technique did not appear to impact on $\dot{V}O_2$ or HR as neither value was significantly different. This suggest that if any learning effect occurred it did not impact on HR or $\dot{V}O_2$ therefore one familiarisation session is appropriate for pitched ladder climbing research.

4.4.2 Effect of Speed

As hypothesised as speed increased the physiological response to the ladder ergometer climbing was greater with significant ($p < 0.05$) increases in oxygen consumption and HR across all speeds. The mean values for oxygen consumption for medium and fast speeds exceeded the current minimum recommended $\dot{V}O_2$ max for working on wind turbines (Renewable UK 2014). At the fastest speed the median reported RPE was 4.0 which was somewhat hard suggesting that individuals were working below maximum. Further investigation when looking at individual cases revealed only one case across the 75 trials at 15.4 m per minute yielded an RPE of 8 (above very hard). Secondly no more than 25% of the sample at 15.4 per minute reported 7.0 (Very hard). This suggests that during pitched ladder climbing an individual's perception of how hard they are working may not necessarily reflect the physiological demand of the task. However, it is difficult to clarify this as $\dot{V}O_2$ max was not assessed therefore making in difficult to ascertain how close to maximum individuals were working. It should be noted the change in RPE was a median increase of 10% between which corresponded to a 19.6% (Slow and Medium) and 11.7% change $\dot{V}O_2$ which does not directly calibrate against the scale. However, it could be of interest in future to do more maximal orientated testing to understand the relationship between RPE and ladder climbing which has not been previously conducted. An increased understanding of RPE and its reliability could be of use to relate to climbing speed, $\dot{V}O_2$ and climbing duration.

4.5 Limitations

The sample population were not accustomed to pitched ladder climbing and this was a new skill learnt for the study by all participants. The recruitment of industry participants may have led to different results as it is hypothesised that those habituated to ladder climbing may have a more economical climbing style. This could potentially have affected results and impacted on the interpretation of the results.

At this current point no industry relevant climbing speeds were known and the research relating to the physiology of pitched ladder climbing was limited. The speeds used in this study were not related to the speeds climbed within the industry as these were not known at this point however, they were based on the work of Kamon (1970). Initially the aim was to cross compare between ladder ergometer studies due to steady state oxygen consumption being achieved which is why the Kamon (1970) speeds were used instead of those by Milligan (2013). In hindsight the use of multiple speeds was appropriate for the research conducted in chapter four but speeds by Milligan (2013) may have been more appropriate as these were slower and would have made the demands of the vertical climbing more manageable (Chapter five).

A final potential limitation is that this reliability study was conducted with the ladder ergometer pitched at 75° and not vertical. This could mean that the reliability may differ when the ladder is vertical but this is speculation as this research was not conducted. It is recognised that whilst conducting this research when the ladder was vertical it would have been more appropriate and more generalisable. However, the timeline within the overall body of work could not accommodate a second reliability study, instead choosing to conduct a pitched versus vertical ladder ergometer study.

4.6 Conclusion

The understanding of reliability is fundamental to understanding learning effects, assessing change and understanding the error within measurements. Pitched ladder ergometer climbing is a skill which, over the course of three trials showed no learning effect, although when using LoA to ascertain reliability demonstrated large within-subject variability. The implication of this study suggests than when aiming to ascertain the effect of an intervention consideration should be given to the error within the measurements to understand whether a true change has occurred. Furthermore, it provides an insight into the potential for false positives and negatives if a pitched ladder climbing fitness test was to be implemented. Nevertheless, whilst this research adds to the current knowledge base surrounding pitched ladder climbing it is not known yet whether this could be applied to vertical ladder climbing. This is an important question as it will ascertain whether research such as this or previous work (Kamon 1970, Kamon and Pandolf 1972, Kamon, Metz and Pandolf 1973) can be used to contribute to an industry which predominately climbs long vertical ladders.

5.0 A comparison of pitched and vertical ladder ergometer climbing

5.1 Introduction

There is an awareness that vertical ladder climbing is a task often faced by those in the wind energy industry (Chapter three; Mette et al. 2017; Garrido et al. 2018). However, an understanding of the demands of vertical ladder climbing is not currently known. To date very little research has focussed on the demands on vertical ladder climbing most likely due to a number of limiting factors: sourcing a venue with the appropriate length and pitch of ladder, costs associated with conducting research in a wind turbine to research purposes, as well as the participants required to comply with all necessary regulations for working at height. All these factors impact on the ability of research to generate reliable data on the physiology of ladder climbing. When research has been conducted on vertical ladders it has been conducted on short ladder with repeated ascending and descending (Vi 2008, Milligan 2013). Although, Milligan (2013) suggested that conducting physiological research on short ladders would fail to show the true demands of vertical ladder climbing. This was hypothesised to due to the partial recovery that occurs whilst descending a ladder as the demand of descending has been shown to reduce oxygen consumption by 45.9% compared to ascending (Barron et al. 2017). Therefore, the use of short ladders when aiming to generate research relating to industries which require long ladder climbing would not be appropriate. An alternative is to conduct research on ladder ergometers that act in a manner similar to a treadmill but for endless pitched ladder climbing.

The use of ladder ergometers for research purposes was established early in the timeline of ladder climbing research with Kamon (1970), Kamon and Pandolf (1972) and Kamon, Pandolf and Metz (1973) all using pitched ladder ergometers. These three studies mentioned investigated ladder climbing at pitches between 60° and 80° but to date no research has been conducted on a vertical ladder ergometer (90° pitch). The use of ladder ergometers allows for the delivery of a constant work requirement enabling steady state oxygen consumption to be achieved. Whilst it also avoids the challenges and regulations of working at height for investigating ladder climbing. However, contemporary and commercially available ladder ergometers are self-standing and not vertical, and require costly modification before users can climb vertically. As a result, most ladder climbing research has been completed either on short fixed vertical ladders (Vi 2008; Milligan 2013) or on pitched ladder ergometers (Kamon 1970, Kamon and Pandolf 1972 and Kamon, Pandolf and Metz 1973).

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

There is an awareness based on the work by Vi (2008) that vertical ladder climbing is more demanding that pitched ladder climbing however, applying this to an industry based on this sole work is inappropriate. Furthermore, this research or that of Milligan (2013) cannot be generalised to long ladders typically used in wind and offshore energy applications, because the research involved short ladder length mandating alternating ascent and descent cycles. Whilst early ladder ergometer research lacked industry specificity because of the non-vertical pitch, which potentially lowers the energy cost (Kamon 1970; Kamon and Pandolf 1972; Kamon, Pandolf and Metz 1973). These shortcomings mean such studies are of limited applicability to the wind energy industry for whom reliable data on the energy cost of vertical ladder climbing are currently unavailable.

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

5.2 Method

5.2.1 Study Design

The study was a crossover design with the order of the speeds randomised within each ladder ergometer pitch (Randomizer.org 2015). All participants completed both ladder pitches with the 75° condition first and the vertical condition second. This was unavoidable due to the modification required to make the commercially available pitched ladder ergometer vertical being irreversible. As a result of this modification process, the minimum time between testing sessions was approximately 21 days. The modification involved stabilisation and re-calibration of the ladder ergometer in a vertical orientation, achieved by placing a wedge underneath its base, and new anchors to the floor, walls and roof (Figure 5.1). All testing took place at the Robert Gordon University, Aberdeen. The School of Health Sciences ethics review panel at Robert Gordon University, Aberdeen approved the study (SHS/15/03).

5.2.2 Participants

Nine healthy male participants with no previous ladder climbing experience were recruited from a student population via emails, posters and word of mouth. All participants were recruited for the study in chapter 4 and were made aware of the potential for ladder modification at the end of testing session three. They were all contacted to invite them to participate in this study once the ladder ergometer had been modified. Participants were emailed a copy of the protocol explaining what would take place and why and given an opportunity to ask questions before agreeing to participate in the study. At this point all participants provided informed consent (Appendix IV) and completed a pre-activity readiness questionnaire (PARQ) (Appendix V). All participants were free to withdraw from the study at any point without providing a reason. Eight participants completed the study and their mean demographics are summarised in table 5.1. All participants completed a pre activity readiness questionnaire (PARQ) and provided informed consent.

Table 5.1 Physical and demographic data of participants (n =8).

Age (years)	Stature (cm)	Mass (kg)
19.8 (±1.7)	178.9 (±6.6)	70.8 (±4.6)

Values are mean and SD

5.2.3 Experimental protocol

All participants were given a minimum of one familiarisation session of ladder ergometer climbing at each pitch with the aim of minimising any learning effect and to ensure they were technically competent and confident at climbing on the ladder ergometer (H/P Cosmos Discovery, Nubdorf, Germany). The ladder ergometer had rung spacing of 24.4 cm and width of 49.5 cm. Participants completed three x 5 minute bouts of climbing at the test speeds with the ergometer being accelerated up to test speed during the first 30 seconds of the 5 minute exercise bout. The order of the speeds was slowest to fastest for familiarisation. These three speeds for the 75° pitch were slow

(9.8 m per minute), medium (12.8 m per minute) and fast (15.4 m per minute). These speeds corresponded to the previous work of Kamon (1970). On the first day of testing, participants had their stature and mass measured and recorded in accordance with a standard protocol (Stewart et al. 2011). Each participant was then fitted with a heart rate monitor strap (Polar FI, Kempele, Finland) that was worn for the duration of the testing session. Participants were familiarised with the Borg (1980) 10 point rating of perceived exertion (RPE) scale before completing a five minute warm up at a self-selected climbing rate no greater than 7.5 m per minute. They then rested for 5 minutes whilst a Cosmed K4 B^2 (Cosmed, Rome, Italy) gas analysis system was fitted to them. This was calibrated prior to each participant following the protocol outlined in appendix VI. At this point the participants were informed of the test order of the speeds they would be climbing at. Participants then completed the three 5 minute climbing bouts with 5 minutes' recovery between each. At the end of each bout of climbing participants were asked for their RPE. $\dot{V}O_2$ and HR were averaged over the last minute of each stage.

Between the first and second testing sessions the ladder ergometer was modified altering the pitch from 75° to 90° (Figure 5.1). The speeds climbed were altered to match the vertical height gained when the ladder was pitched, as shown by equation 6.

$$\text{Vertical speed} = (75° \text{ climb speed}) * (\sin 75) \qquad \text{[equation 6]}$$

The corresponding speeds for slow, medium and fast speeds were 9.5, 12.4 and 14.9 m per minute. Participants were familiarised at these speeds following the same process as per the initial familiarisation at 75°. A minimum of 24 hour later the participants returned to complete the testing session.

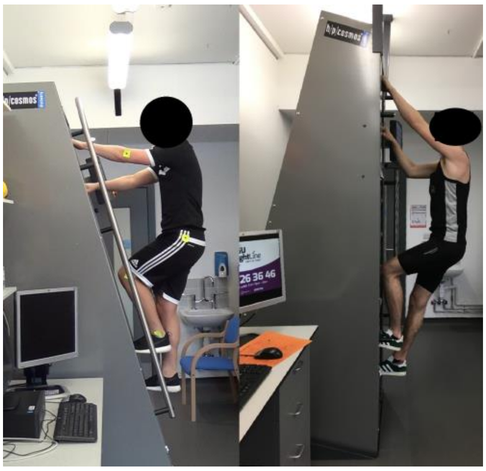

Figure 5.1. H/P Cosmos Discovery ladder ergometer pre and post modification.

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

5.2.4 Statistical Analysis

All statistical analysis was conducted using SPSS V.21 (IBM, Armonk, USA). Descriptive statistics were calculated for the sample group and normality assessed using the Kolmogorov-Smirnov test (Field 2012). A sensitivity analysis was run to determine the effect of non-normally distributed variables and the effect of box-Cox transformation in order to determine if variables could be treated as normally distributed. A factorial repeated measures ANOVA was run in order to identify the effect of both speed within each ladder pitch condition, and the effect of the change of pitch on $\dot{V}O_2$ and HR. Mauchley's test was used to assess sphericity and if this was violated, the Greenhouse-Geisser test effect values were used (Field 2012). Significant main effects of ladder pitch were explored using a paired t-test with significance set at $p < 0.017$ due to multiple pairwise comparisons. Effect sizes for the effect of the change on ladder pitch within each speed were calculated using Cohen's d and interpreted using guidelines set out by Winter, Abt and Nevill (2014). A statistical model comprising a Chi-Squared test, factorial repeated measures ANOVA and if significant main effects were seen then a paired t-test was used to assess the effect of ladder pitch on RPE. Significance was set at $p < 0.05$ for the Chi-Squared test and the factorial repeated measures ANOVA and $p < 0.017$ for the paired t-test to account for multiple comparisons. Comparisons between non-normally distributed variables were assessed using the Wilcoxon signed rank test.

5.3 Results

The sensitivity analysis suggested all data could be treated as normally distributed. For $\dot{V}O_2$ there was a significant interaction effect observed between climbing angle and speed $F(2,14) = 7.8$. Further analysis highlighted that an interaction was present between climbing angle and the slow and medium speeds ($p < 0.01$) but not the medium and fast speed. A significant ($p < 0.05$) main effect for climbing speed, $F(2,14) = 495.8$ and climbing angle, $F(1,7) = 79.9$ were observed. Contrasts revealed that climbing vertically significantly increased $\dot{V}O_2$ $F(1,7) = 79.9$ compared to at 75° as well as highlighting that $\dot{V}O_2$ consumption was significantly higher in the fastest speed compared to the slowest in addition to being significantly higher than the medium speed.

Further pairwise analysis, as shown in figure 5.2, was conducted within each speed showed that climbing vertically led to a significant increase $\dot{V}O_2$ consumption compared to at a 75° pitch. $\dot{V}O_2$ increased by 7.9 (± 1.8) $ml.kg.min^{-1}$ at the slow speed whilst at the medium and fast speeds by 6.3

(±2.2) ml.kg.min^{-1} and 5.1 (± 2.8) ml.kg.min^{-1} respectively. The corresponding effect sizes were all large, as shown in table 5.2.

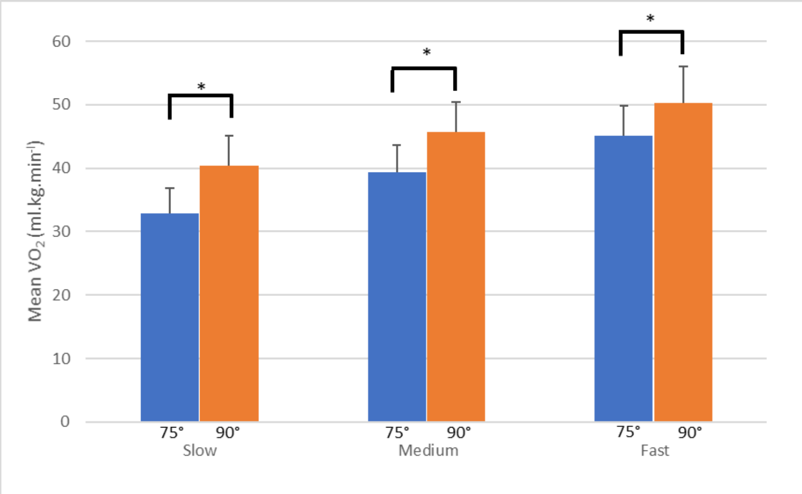

Figure 5.2. Mean $\dot{V}O_2$ response to the change in ladder ergometer pitch * denotes significance ($p < 0.017$).

There was significant interaction effect observed for the angle and climbing speed for HR with further analysis showing significant interaction effects between angle and climbing speed. This was seen for both the angle and slow and medium speed interaction as well as the angle and medium and fast speed interaction. Significant main effects for HR were seen for both speed, $F(2,14) = 103.8$; and angle, $F(1,7) = 41.6$. Comparisons showed that HR significantly increased when the speed increased and that it also increased when the angle was changed to 90°. Pairwise analysis, as shown in figure 5.3, showed that HR significantly ($p < 0.017$) increased at all speeds when climbing vertically compared to when pitched at 75°.

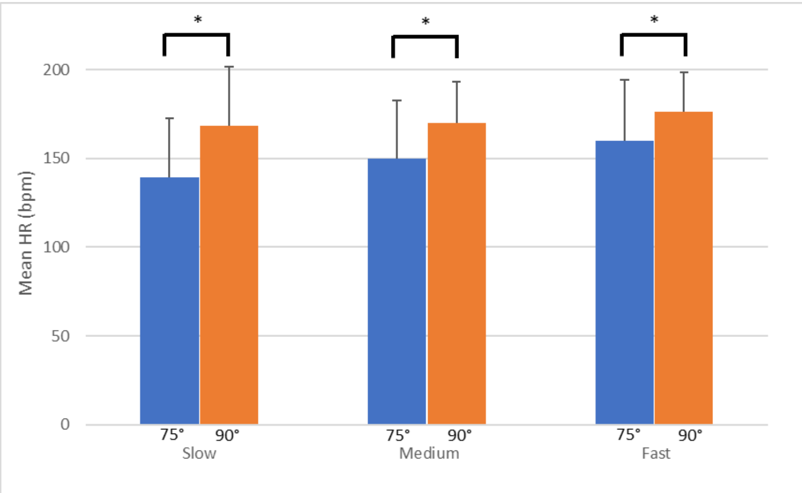

Figure 5.3. Mean HR response to the change in ladder ergometer pitch * denotes significance ($p < 0.017$).

HR increased by 29.3 (± 10.5) bpm, 20.0 (± 10.0) bpm and 16.7 (± 10.8) bpm for the slow, medium and fast speeds between the conditions. The effect of the change of ladder pitch on HR showed a large effect at all speeds, as shown in table 5.2.

Table 5.2. Effect sizes for change of ladder ergometer pitch on $\dot{V}O_2$ and HR.

	$\dot{V}O_2$ (ml.kg.min^{-1})	Heart rate (bpm)
Slow	3.3	1.9
Medium	1.9	1.7
Fast	1.7	1.5

The median RPE for the slow, medium and fast speeds at 75° were 1.5, 3.0 and 4.5 respectively. After the ladder was made vertical the median RPE for the three speeds were 4.5, 5.0 and 7.0 respectively. No interaction effect was observed between speed and angle for RPE. However significant main effects were seen for both angle and speed. Further pairwise analysis showed that modifying the angle of the ladder ergometer significantly increased RPE at the all speeds ($p < 0.017$).

5.4 Discussion

This study aimed to ascertain whether modifying the pitch of a ladder ergometer from 75° to 90° altered the physiological response to ladder ergometer climbing at matched vertical speeds. It was found that climbing in the 90° orientation was associated with significantly higher oxygen consumption across all speeds as well as significantly higher HR in the slow and medium speeds. The mean increase in $\dot{V}O_2$ between the ladder pitch conditions was 17.3% whilst within each of the three speeds $\dot{V}O_2$ increased by 24.5%, 16.0% and 11.5% for slow, medium and fast speeds respectively. In comparison to Kamon (1970) (for similar speeds but at a 60° pitch) the reported $\dot{V}O_2$ values here are higher across all speeds and at both pitches with Kamon (1970) reporting means of 27.0 (± 0.7) ml.kg.min^{-1}, 32.9 (± 1.2) ml.kg.min^{-1} and 39.6 (± 2.7) ml.kg.min^{-1} for slow medium and fast speeds respectively. Due to the consistent nature of the speeds between the present study and Kamon (1970) and the lower $\dot{V}O_2$ values reported by Kamon (1970) clearly ladder pitch increases the energetic demand of climbing. This could be in part due to biomechanical alterations such as the height at which the rungs are grasped, the foot-hand distance, the change in the position and movement of the centre of mass (COM) and the requirement to maintain balance (Bloswick and Chaffin 1990; Hammer and Schmalz 1992). Hammer and Schmalz (1992) reported that as ladder pitch increased the proportion of time with three points of contact also increased significantly. They hypothesised this to be due to the need to maintain balance. Figure 5.4 shows the change in ladder pitch may alter the COM bringing it outside the base of support as well as reducing the area of the base. Whilst a similar figure was depicted by Hammer and Schmalz (1992) it highlights the displacement of the COM is due to a change in ladder pitch.

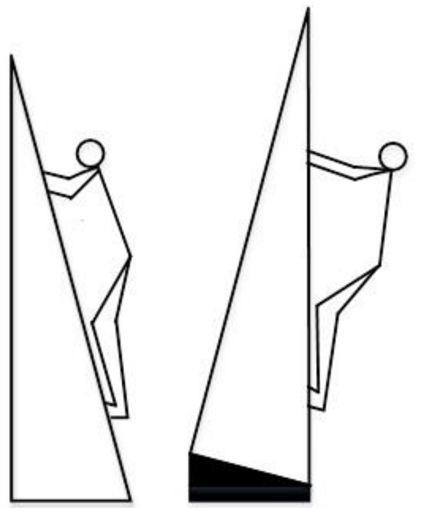

Figure 5.4. Change in body position in response to ladder ergometer modification.

The change in ladder pitch may alter the mechanical work completed for a given height with climbers having to continually displace their centre of mass vertically upwards. Combined with the COM being outside the base of support, this may lead to increased muscular activation compared to 75° climbing, increasing the physiological cost of climbing. This increase in demand, shown as increased $\dot{V}O_2$ consumption and HR, may be based on the increased requirement to actively maintain stability due to the position of the COM being outside of the base of support. Furthermore, it may also be due to the increased mechanical work to move the COM vertically with every climbing cycle. To overcome this change of stimulus climbers have been shown to adapt their climbing gait and cadence in order to maximise the contact time with ladder to maintain balance (Hammer and Schmalz 1992). The increased contact time and the relative position of the COM to the base could potentially exacerbate forearm stress underpinning localised fatigue or increased EMG readings in vertical climbing (Bloswick and Chaffin 1990; Hammer and Schmalz 1992; Vi 2008; Oksa et al. 2014). Oksa et al. (2014) found that mast climbers wrist flexors and extensors mean muscular strain was 24 ± 1.5 % maximal electrical myography (MEMG) and 21 ± 1.0 %MEMG respectively. Both values exceed the recommended of occupational work exceed 14 %MEMG. Taken together this suggests that the shift from pitched from vertical ladder climbing increases the strain on the muscles within the forearm which is felt as localised soreness fatigue in the forearms. This may in part also contribute to the larger than proportional increase in RPE relative to $\dot{V}O_2$ between the pitches. Median changes of RPE were 3.0, 2.0 and 2.5 units respectively compared to 24.5%, 16.0% and 11.5%

increases in $\dot{V}O_2$. Therefore, whilst the exercise modality is similar the change in pitch alters perceived effort and further highlights the necessity for specificity when conducting research relating to ladder climbing. Although not investigated in the present study, it is suggested that the need to maintain balance may in part cause greater muscular activation therefore increasing the energy demand of vertical climbing in comparison to pitched ladder climbing and affect perceived exertion.

This current study supports the research conducted by Vi (2008) that vertical ladder climbing has a higher physiological cost than that of a 75° pitched ladder. Vi (2008) reported an 8.5% increase in HR when climbing vertically compared to a pitched ladder which was lower than this study where the mean change was an increase of 15.8%. The current study reported greater increases in HR than those of Vi (2008) with changes of 22.1%, 14.0% and 11.2% being observed from the slowest through to the fastest speed versus 8.5%. There may be numerous reasons for the differences this study and that of Vi (2008), such as the length of ladder, the total duration climbed however, the main influencing factor is most likely the continual 5 minutes of ascending. It should be noted that the speed at which Vi (2008) used was not reported therefore could differ from this study. The present study, by the use of a ladder ergometer, had participants ascend for the duration of the exercise bouts rather than alternating ascending and descending a short ladder, as in Vi (2008). Descending a ladder had been shown to reduce $\dot{V}O_2$ consumption by between 23% and 46% compared to ascending (Kamon 1970; Barron et al. 2017) which may partially explain the difference larger difference in the values between this study and those of Vi (2008). Furthermore, Milligan (2013) had individuals climb at 10.52 m per minute eliciting a mean $\dot{V}O_2$ of 28.6 ml/min/kg which is considerably lower than that observed during the 9.52 m per min in the present study of 40.7 ml.kg.min^{-1}. Although participants in the current study climbed at a faster rate than those in the study of Milligan (2013), the large difference in oxygen utilisation between the studies is most likely explained by the partial recovery during descending involved in their study.

Taken together, this study supports the premise that vertical ladder climbing does have a greater physiological strain than pitched ladder climbing and also indirectly highlights the effect that descending may have on physiology-related ladder climbing studies. This highlights the need for specificity in relation to industry requirements, recognising the uniqueness of longer ladder climbing and the physiological consequences of longer ascents, compared to shorter repeated ascents. Therefore the adoption of a fitness standard from any other industry that does not predominately climb long vertical ladders would be inappropriate due to reduction in measured demands by comparison.

5.5 Limitations

Due to the procedures involved in modifying the ladder ergometer and the subsequent approval by a structural engineer it was not possible to specifically identify the time period between the two testing sessions. This time was a minimum of three weeks and between the pitched and vertical testing sessions there was no significant change ($p > 0.05$) in body mass for the sample group. Therefore, it was deemed that the participants were most likely in a similar physical fitness condition compared to when they undertook the first testing session.

It is appreciated that wind turbine technicians, and others who climb vertical ladders, may use the rails of the ladder. Due to the design of the ladder ergometer it was not possible to have rails fixed to both sides of the ladder ergometer. Previous research has been conducted using both the rungs and the rails (Armstrong et al. 2009; Pliner, Campbell-Kyureghyan & Beschorner 2014) of the ladder but Armstrong et al. (2009) suggest that the grip is better when using the rungs. Therefore, it was not deemed to have a negative impact on the study.

As outlined the section 4.2 the speeds used were based on and piloted from work completed by Kamon (1970), which were deemed appropriate for when climbing at 75°. However, when altering the ladder ergometer to 90° these speeds were faster than would potentially be used in the industry. In the present study the medium and fast speed were faster than the recommended and emergency speeds suggested by Milligan (2013). This meant that one participant was unable to complete the full testing protocol at 90˚, reducing the sample size available. This research showed an interaction between speed and pitch therefore it would be anticipated that at slower real-world speeds there would still be a significant increase in physiological demand at slower speeds.

5.6 Conclusion

Climbing a ladder ergometer at 90° has an increased physiological demand compared to that at 75° which has implications when ascertaining a fitness standard or cross comparing the demands of industries. It highlights that it is inappropriate to adopt fitness standards from industries that predominately use pitched ladder, such as the fire and rescue service and reiterates the requirement for a bespoke fitness standard for wind energy industry. The increased demand most likely results from the altered the position of the COM, which necessitates climbers adapt their technique to maintain balance, affecting their contact time with the ladder and increased muscular activation and physiological strain. In contrast to previous research (Vi 2008; Milligan 2013) steady state vertical climbing demands higher values of $\dot{V}O_2$ and HR compared to a combination of ascending and descending for the same duration at similar rates. Long vertical ladder climbing is most likely a critical task for wind turbine technicians and commonly takes place within the industry (Chapter three, Garrido et al. 2018) and this research highlights that due to the length and pitch of the ladder that the activity is unique. This reinforces the need that the industry should follow best practice (Petersen et al. 2016) with future research specific to the requirements of the industry that should aim to inform policy and standards in relation to climbing long vertical ladders. Therefore, it is necessary to understand how industry relevant factors such as climb assist may reduce the demand of climbing and whether the addition of external loading or a space restriction also alter the demand of vertical ladder climbing.

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

6.1 Introduction

Chapter three identified that ladder climbing has many different areas to be investigated (Figure 3.6) and that it is a complex, challenging and physically demanding task (Mette et al. 2017; Barron et al. 2018). There are several factors that could have a positive and negative impact on the demands of ladder climbing. It is necessary to have a fuller understanding of all factors relating to ladder climbing when potentially looking to alter or develop a physical employment standard (Petersen et al. 2016). Furthermore, a greater understanding of these factors could have short- and long-term impact on those who climb ladders within the wind energy industry. An example of this is the development of climb assist devices which claim to have a positive impact on those required to climb ladders. The work in chapter three identified that only 25% of those who responded to the survey reported that climb assist devices were in place in the turbines they climbed. Personal communication suggested that these are not more widely employed due to the lack of evidence pertaining to the effect of climb assist devices even though they claim to reduce physical strain.

It has previously been outlined that there is a lack of research on the demands of vertical ladder climbing. However, in response to the wind energy industry, companies have developed and produced devices which aim to reduce the effort of climbing vertical ladder. Devices such as these are known as "climb assist" devices which aim to provide mechanical uplift that aims to aid upward progress (Figure 6.1).

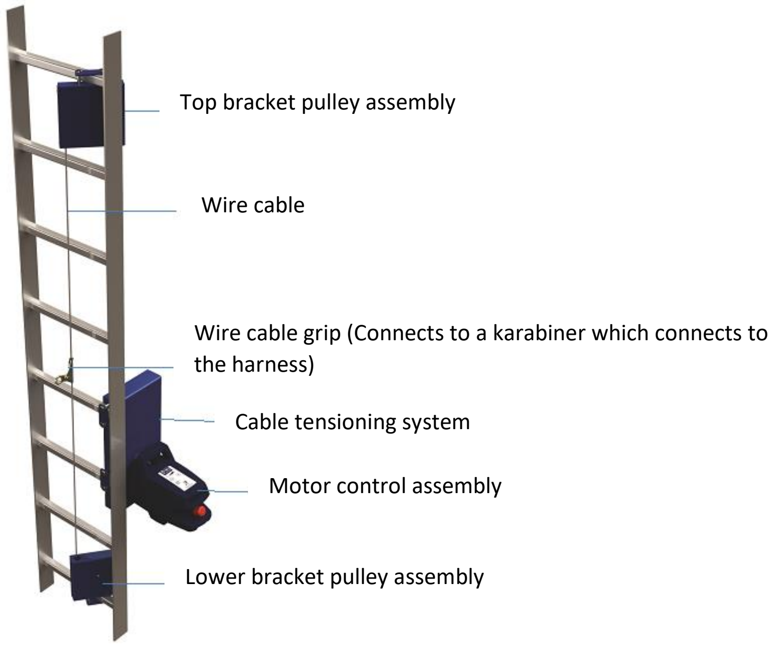

Figure 6.1 Climb assist system (Permission to reproduce figure from Capital Safety 2015)

Whilst aiding climbers with mechanical uplift these systems have other uses such as fall arrest systems and the ability to carry loads up the towers (Siemens 2012, Limpet 2015). Climb assist systems respond to the climbing speed and the level of assistance is adjustable with the range of support differing between the manufacturers. The level of assistance, which is delivered by a motor connected via a wire cable, may reduce body mass by up to 90% with ranges of 26 – 126 kg although this varies depending on the manufacturer (Capital Safety 2015; Limpet Technology 2015). The assistance provided by such systems has led to promotional material claiming that they have the ability to "reduce worker fatigue" or "increasing productivity and asset availability" (Siemens Technology 2012; Capital Safety 2015; Limpet Technology 2015). To date there has been no published research investigating the effect of climb assist devices, therefore such claims are unsubstantiated. The undertaking of research that investigates the effect of such devices could have implications for both research and practice. The knowledge gained from such research may impact professional practice within the wind energy industry as the production of research would give the industry scientific evidence to make a more informed decision on the implementation of these climb assist devices. Therefore, the aim of this study is to ascertain the effect of the climb assist device on $\dot{V}O_2$, heart rate (HR) and rating of perceived exertion (RPE) during vertical ladder climbing. These outcome measures were chosen as it was possible to assess these in the field and can be related to the medical fitness standard. Furthermore, the use of RPE is of interest to ascertain whether the change in RPE is relatable to the change in $\dot{V}O_2$. The ability to explore the effect of climb assist on biomechanics was not feasible due to the location being a 30 m wind turbine which would have led to magnetic interference with the system used for biomechanical analysis and no relevant data would have been gathered. It was hypothesised that using climb assist would lead to a reduction in $\dot{V}O_2$ consumption, HR and RPE.

6.2 Method

6.2.1 Study Design and Justification

The study was a repeated measures randomised crossover design with the order of the testing conditions randomly ordered by randomized.org. This aimed to minimise any confounding effect relating to the order of tests. All participants completed a vertical climbing test in two conditions (with and without climb assist) and measurements of $\dot{V}O_2$, HR and RPE were taken. These measures were able to be practically conducted in a field environment and could be compared against the current medical fitness guidelines. The study was approved by the local university ethics committee at The Robert Gordon University, Aberdeen (SHS/15/23). All testing took place at the 3M safety training facility, near Oldham.

6.2.2 Participants

Participants were recruited via convenience sampling by Capital Safety with whom the study was run in conjunction with. Capital Safety had access to experienced ladder climbers and could recruit from those who worked at the site. In advance of undertaking the study all the study information was circulated to a gatekeeper including the participants information sheet (Appendix VII). Eight participants (six male and two female) with previous ladder climbing experience volunteered to take part in the study. The mean demographic data for each gender are shown in table 6.1. All participants read the participant information sheet (see appendix VII) and had the opportunity to have all their questions answered before completing a PARQ (see appendix VIII) and providing informed consent (see appendix IX). All participants were required to answer "No" to all questions on the pre-activity readiness questionnaire (PARQ) or provide justification of a yes before they were deemed healthy to participate in the study. Therefore, all participants were deemed to take healthy to take part in the study with no history of recent injury and all participants provided informed consent.

Table 6.1. Mean demographic data

Gender	Age (years)	Stature (cm)	Mass (kg)
Female (N=2)	31.4 (±4.2)	169.8 (±16.8)	64.8 (±14.6)
Male (N=6)	39.6 (±12.6)	181.2 (±7.0)	93.8 (±16.3)

6.2.3 Experimental Protocol

Prior to testing taking place participants had their stature and mass measured and recorded according to standard ISAK protocols (Stewart et al., 2011). In addition, participants were explained the testing procedure and familiarised with the Borg 10-point RPE scale (Borg 1980). Before warming up participants were fitted with a Polar FT90 (Polar Fi, Kempele, Finland) heart rate monitor watch and chest strap (Polar Fi, Kempele, Finland) to measure and record their heart rate throughout the testing. Participants wore a full body harness (Capital Safety, Oldham, United Kingdom) throughout the testing, which was connected to a fall arrest system at all times when climbing. Participants warmed up by climbing vertically (30 m) without climb assist in time with a metronome (Finis, Livermore, USA) set at 24 beeps per minute to facilitate a climbing speed of 24 rungs per minute. Participants then also descended at the same rate as part of the warm up. This climbing rate was slower than their habitual climbing rate but it was selected as it had previously been used by Milligan (2013) as the minimum acceptable climbing rate for the oil and gas industry. The warm up also allowed participants to familiarise themselves with the rate of climbing required for the testing. The ladder climbed was 30 m in length, constructed from aluminium with a rung spacing of 28 cm with the rungs being 42 cm wide. The cross section of the rung was 2.5 cm high and 3.0 cm deep. The ladder was positioned in the centre of the tower of a non-functional wind turbine used for training purposes at the 3M training facility near Oldham. Following completion of the warm up participants had a five minute rest during which the Cosmed K4 B^2 system (Cosmed, Rome, Italy) was fitted before initiating data collection. The system was calibrated prior to each participant following the protocol outlined in Appendix VI. At this point participants were informed of the order they would be climbing with either the climb assist or the non-assisted condition first.

The climb assist system used throughout was the “Powered Climb Assist Tower Kit” (Capital Safety, Oldham, United Kingdom). The level of climb assist was set to 35 kg for most participants (N = 6), although the heaviest and lightest participants (122.6 and 54.4kg) selected 55 kg and 22 kg, respectively. The heaviest and lightest participants self-selected their level of assistance whereas, all other participants used the mid setting of the system. The mean assistance was equivalent to 42.3% of body weight. The climb assist system was connected to the participants at the hip contact points on the harness when in use. Participants then ascended and descended a 30m ladder inside a wind turbine at a rate of 24 rungs per minute with most taking approximately three minutes and 45 seconds to complete one full ascent and then the same time for a full descent. $\dot{V}O_2$ consumption and HR were measured throughout with the last minute of each ascent and descent averaged to find the mean $\dot{V}O_2$ and heart rate. After each climb participants were asked for their RPE for the ascent and descent on the Borg 1-10 scale (Borg 1980). Participants had a 5 minute rest before repeating the procedure in the second test condition which was dependent on the randomly assigned order.

6.2.4 Statistical Analysis

All statistical analysis was conducted using SPSS V.21 (IBM, Armonk, USA). Descriptive statistics including the mean and standard deviation were calculated for demographic data for each gender. Kolmogorov-Smirnov test was run to assess the normality of mean $\dot{V}O_2$ and mean HR for both test conditions as well as for ascending and descending. A paired t-test was run in order to assess the difference between the test conditions for mean HR and $\dot{V}O_2$ whilst the difference between the conditions was also assessed using effect size. Cohen’s d was used to interpret the magnitude of difference between the testing conditions for HR and $\dot{V}O_2$ with the magnitude of change being assessed in line with guidelines outlined by Winter, Abt and Nevill (2014). The change in RPE was assessed using the Wilcoxon’s signed rank test (Vincent and Weir 2012).

6.3 Results

6.3.1 Effect of climb assist

Due to technical issues with the Cosmed K4B^2 which led to an unexpected loss of data the full data set was not available for analysis. Therefore only 6 pairs of data were available for analysis for both $\dot{V}O_2$ and HR with mean demographics shown in table 6.2. This led to a smaller than anticipated sample size however, both $\dot{V}O_2$ and HR were normally distributed making it appropriate to conduct parametric tests.

Table 6.2. Mean demographic data for six participants

Gender	Age (years)	Stature (cm)	Mass (kg)
Female (N=1)	34.3 (±0.0)	181.5 (±0.0)	75.1 (±0.0)
Male (N=5)	36.6 (±11.6)	183.2 (±7.4)	95.6 (±17.5)

The use of a climb assist significantly ($p < 0.05$) reduced the oxygen cost of ascending compared to without climb assist (22.0 ±4.3 $ml.kg.min^{-1}$ vs. 28.3 ± 3.5 $ml.kg.min^{-1}$) as seen in figure 6.2. The mean reduction in $\dot{V}O_2$ was 22.5% with an effect size of 1.80, a large effect.

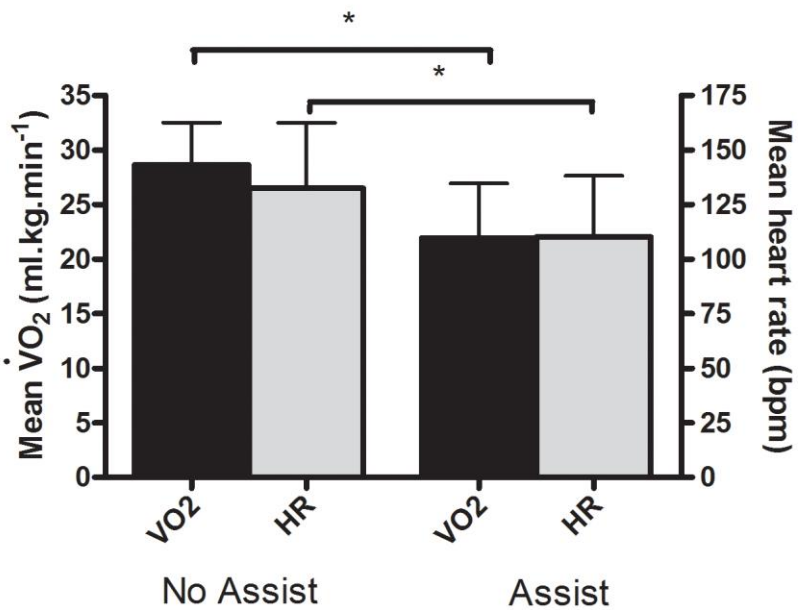

Figure 6.2 Effect of climb assist on $\dot{V}O_2$ and HR

HR significantly decreased from 134 ± 27 bpm to 114 ± 26 bpm ($p < 0.05$) when using climb assist, as seen in figure 6.2. This was equivalent to a moderate effect size of d = 0.75. The mean decrease in heart rate was 14.8% when using climb assist although the decrease ranged from 0.4 – 25.7 %. RPE

(N = 8) significantly ($p < 0.05$) decreased from a median of 3 without climb assist to 1 with climb assist. The change in RPE ranged from no change to a decrease of 3 points.

The mean $\dot{V}O_2$ consumed for descending was 13.8 ± 2.4 $ml.kg.min^{-1}$ with climb assist and 15.3 ± 3.7 $ml.kg.min^{-1}$ without climb assist. No statistically significant differences were found between climb assist and no climb assist when descending ($p > 0.05$). There was a statistically significant decrease in heart rate from 111 ± 26 bpm with no climb assist to 99 ± 27 bpm with climb assist. This equated to a moderate effect ($d = 0.45$). RPE was also statistically significantly reduced when descending with climb assist ($p < 0.05$). The median RPE for participants reduced from 2.5 to 1 when using climb assist.

6.3.2 Comparison of ascending and descending

The mean for ascending without climb assist for $\dot{V}O_2$ was 28.3 ± 3.5 $ml.kg.min^{-1}$ which was significantly higher ($p < 0.01$) than that of descending 15.3 ± 3.7 $ml.kg.min^{-1}$ with a corresponding large effect of $d = 3.2$. Whilst HR decreased from 132.4 bpm (± 28.6) to 99.0 bpm (± 26.8) which showed a moderate effect of 0.75. The change in RPE was significantly reduced from a median of 3.0 to 1.0.

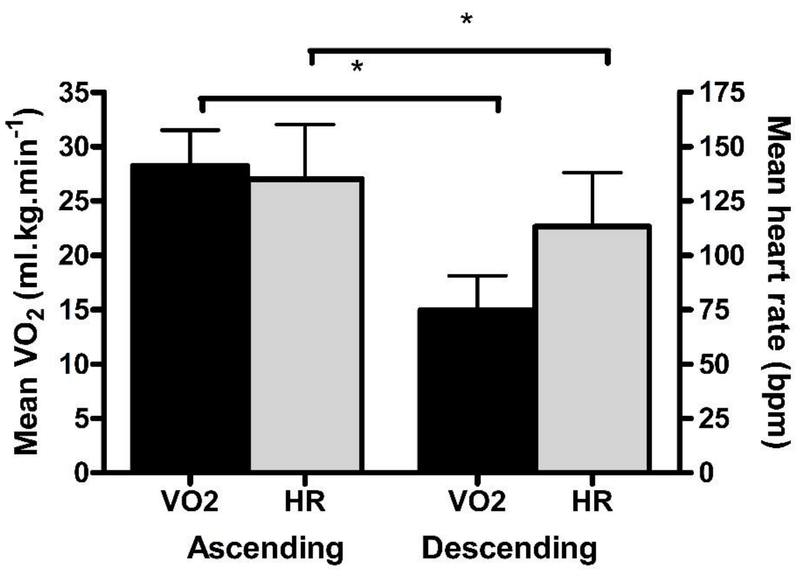

Figure 6.3 Effect of climb direction on $\dot{V}O_2$ and HR

6.4 Discussion

6.4.1 Effect of climb assist

Climb assist systems claim to reduce the strain on individuals when climbing and this study found that using such a system significantly reduces oxygen consumption, HR and RPE when climbing vertically upwards. The use of a climb assist device had a large effect on $\dot{V}O_2$ with a 22.5% reduction observed which mapped against a 2.0 unit reduction in $\dot{V}O_2$ showing a proportional decrease in RPE. Whilst, a moderate effect was observed on HR with a 14.9% decrease. These mean changes are lower than the mean level of assistance provided by the climb assist device (43% of body mass) and this may be due to the need to maintain stability which requires the exertion of horizontal forces (Armstrong et al. 2009). Vertical ladder climbing is an activity which requires individuals to repetitively exert forces large enough to displace their centre of mass (COM) from one rung to the next. This requires individuals to overcome gravity and accelerate their COM to the next rung of the ladder. The required mass to be overcome may be reduced when climbing with a climb assist device due to the device providing upward lift. It is hypothesised that by reducing the weight an individual must displace this would lead to a reduction in the force required to move and therefore lower the energy demand of climbing. It should be noted that the climb assist device used in this study provided continuous assistance which is unlike the effort of ladder climbing which is discontinuous however, the discontinuous nature may alter depending on climbing speed and cadence. This meant that the assistance was only provided when the participants were moving at a minimal speed rather than providing continuous upwards traction. It was observed that due to the climbing rate used in this study that individuals had to pause on each rung or reduce their cadence from normal to ensure they met the required climbing rate; a faster climbing rate or self-selected rate could lead to a more continuous climbing style. This occasionally meant that the climb assist system paused and required a small downwards movement of the COM to reactivate it. It could be hypothesised that the reduction in $\dot{V}O_2$ and HR may correspond to the decreased muscular activation in line with a reduction in the force produced and cardiac output. However, this is only hypothesised and future work on muscular activation and force production should be conducted in order to more fully understand the effects of climb assist devices.

Whilst this study showed that climb assist devices may have acute positive impact on the demands of ladder climbing caution should be taken with the long-term impact. These devices work by using power and if the turbine is in low power mode climbers would be unable to use the system. If those individuals adapted to climbing with climb assist every time and then were required to climb without it this would potentially be more harmful that having climbed without it and having adapted to do so. The impact of such devices does require longitudinal investigation as the long-term implications and adaptations of climb assist systems are unknown.

6.4.2 Vertical Ladder climbing

This is the first study that has investigated vertical ladder climbing over an extended period of time with most previous research having been conducted on short (< 5 m) vertical ladders, pitched ladders or ladder ergometers (Kamon 1970; Kamon and Pandolf 1972; Bilzon et al 2001; Vi 2008; Milligan 2013). This, as outlined previously, is often due to logistical issues surrounding conducting research on long vertical ladders or the cost associated with modifying ladder ergometers. Milligan (2013) found lower mean $\dot{V}O_2$ values when climbing at 24 rungs per minute of 23.6 ml.kg.min^{-l} compared to this study's value of 28.9 ml.kg.min^{-l}. A potential explanation for the difference between the results could be due to the protocol and the total height climbed. When comparing the total height climbed between this study and Milligan (2013) it was observed that although the climbing rate was matched due to differences in ladder construction this lead to Milligan's participants climbing 7.32 m per min rather than 6.32 m per minute. This point provides a learning point for professional practice or research that whilst a set standard step rate may be easier to administer it is rung spacing dependent. If this is extrapolated to climbing an 80 m wind turbine the same step rate would lead to a one-minute difference in time to complete climbing the ladder (11.9 min v 10.9 min). Therefore, when designing test protocols, the interaction of climbing rate and rung spacing should be taken into consideration.

Intuitively the higher climbing rate in meters would suggest that the mean $\dot{V}O_2$ should be higher for Milligan's (2013) study compared to this study. The protocols differed with participants repeatedly ascending and descending a 5 m ladder for three minutes (Milligan 2013) and as highlighted in figure 6.3 descending has a significantly lower demand than that of ascending. This current study observed a 45.9% reduction in oxygen consumption when descending compared to ascending which was lower that reported by Kamon (1970) who reported descending to have a net $\dot{V}O_2$ of 24% of that of ascending. Although it should be noted that Kamon (1970) reported this on a 60° ladder ergometer and this change was not consistent across all speeds with some showing no change. Even though such a finding is inevitably limited in terms of generalisability by this small sample, the emerging picture suggests the difference in ladder climbing demand between this study and that of Milligan (2013) is due to systematic differences in the protocol. This is because Milligan's study required participants to descend a ladder for about 50% of the time for data capture, lowering the mean steady state $\dot{V}O_2$ value. Furthermore, participants in the current study climbed continuously for almost 4 minutes which would allow for steady state oxygen consumption to be nearly achieved. Based on work by Burnley and Jones (2007) they stated that in the moderate exercise domain that steady state oxygen consumption could occur. However, it should be noted that Astrand and Rodahl (1986) suggested that exercise bouts should aim to be 5 minutes long although they did recognise that steady state oxygen consumption could occur at 3 minutes. The use of a longer ladder would have increased the time participants climbed at steady state however, sourcing a venue with a ladder of such a length is difficult as no research to date has used such a ladder.

6.4.3 Ascending v. Descending

It is generally assumed that descending a ladder has a reduced demand than ascending a ladder as individuals are required to move with gravity rather than overcome gravity. This study found that the direction of climbing had a large effect on both heart rate on $\dot{V}O_2$ (d = 3.5) and HR (d = 0.81) with reductions in $\dot{V}O_2$ and HR of 46% and 16%. It should be recognised that the HR and $\dot{V}O_2$ at the start of each direction of the climb different due to the activity directly prior to the ascent or descent. For example, this meant that the HR and $\dot{V}O_2$ at the start of the descending phase were higher than that at the start of the ascent phase due to five minutes rest having taken place before this instead of a ladder climbing ascent. However, no expected impact was thought to occur due to the sample population being habitual ladder climbers and the analysis taking place in the final minute of each climb direction. This allowed for the measured variables to lower and achieve the appropriate steady state in time for analysis. The reduction in HR differs from the finding of Kamon (1970) when descending a 60° ergometer who found that there was not a difference when ascending and descending at high speed although, the speed at which this occurred was not reported. Kamon (1970) also stated that HR analysis for a comparison of ascending and descending at slower speeds was not possible due to the speed of the ergometer. Although the speeds which they used appear to be low with vertical climbing rates as low as 4 m per minute (Kamon 1970, Figure 1). A potential reason for this might be that at high speeds individuals have to work hard to maintain their position on the ladder ergometer which could lead to an elevated HR compared to lower speeds. Further to this vertical ladder climbing is significantly more demanding than pitched therefore potentially the increased demand observed by the ladder pitch is the main factor in difference between the observations seen by Kamon (1970) and this study. Therefore, the difference in ladder pitch could be a confounding variable affecting the difference in the effect of direction of travel as the body must also travel horizontally. The unique nature of the role of a wind turbine technician has previously been recognised this finding has an implication from the perspective of applying research to practice. This study highlights the difference in demands between ascending and descending which underlines the premise of specificity of testing relating to the appropriate industry. If research studies are conducted on short ladders which requires repeated ascending and descending any generalisations to wind energy on this research this would underestimate the demand of vertical ladder climbing by comparison to research conducted on long ladders. Therefore, based on this, research which aims to the contribute to practice or knowledge in occupational physiology of wind energy should be based on extended periods of vertical ladder climbing rather than repeated ascending and descending.

6.5 Limitations

Due to the nature of the study and the convenience sampling involved this limited the study's sample size and its generalisability. Only six pairs of data were available for heart rate and $\dot{V}O_2$ comparison due to technical issues with equipment. However, the data were still normally distributed allowing for the use of paired t-tests and effect size calculations.

Perplexing was a small increase in oxygen cost with climb assist in one individual, who was used to much faster climbing speeds. Individual variability, as in locomotion, in preferred speed is likely to influence oxygen cost and efficiency, which merits further investigation, especially in workers of different size and fitness (Sparrow 2000).

Measuring the effect of climb assist on force vectors, centre of mass and biomechanics would have provided a more complete picture of the effect of climb assist on climbing. However, due to environmental factors it was not possible to measure the appropriate variables to conduct analysis on these topics. However, the nature of the climb assist involves direct force applied to the wearer's main harness karabiner at the hips, at an angle of less than vertical. Therefore, the horizontal component of this angle pulls the wearer towards the ladder.

6.6 Conclusion

Climb assist devices are relatively new systems which have the potential to benefit both climbers and wind turbine service providers alike by reducing the energetic cost and effort of climbing wind turbines. At the minimum accepted climbing rate the system appears to have a positive effect on vertical climbing and future research should aim to establish the wider effect of such systems with different speeds, longer ladders and the impact on long term work and recoverability. Initially, these systems do appear to have a positive impact although more research is required to more fully understand the effects. The implication of this has yet to be considered in a more broader setting as the wide ranging use of devices could have both positive and potentially negative impact on wind turbine technicians.

Wind turbine technicians have already been identified as having a unique demands placed on them (Chapter 3; Mette et al. 2017; Garrido et al. 2018) however, this study outlines how different environments and methods may impact the generalisability of research. As expected descending a long ladder had a decreased demand by comparison to ascending. Therefore, this suggest that it would be inappropriate to generalise research that has been conducted short ladder using repeated ascents and descents to that of long ladder climbing as it has a lower mean demand. Although this finding is observed in a small sample size (n = 7) it nevertheless outlines an importance considering when conducting research with the aim of generalising to an industry that specificity is key.

The use of the climb assist device has been shown to reduce the demand of vertical ladder climbing but as outlined in chapter three other factors could potentially increase the demands of ladder climbing. These factors may include the addition of an external load or space restriction when climbing. This study is one piece of a larger puzzle which still has many pieces to be considered when understanding the demands of climbing but highlights the impact that one external influence could have on the demands of vertical ladder climbing.

7.0 The effect of external load carriage and space restriction on vertical ladder ergometer climbing

7.1 Introduction

As outlined in previous chapters it is necessary to have a more complete understanding of the demands of an occupation before designing and producing a physical employment standard (Peterson et al. 2016). Chapter three identified that the maintenance of a wind turbine required individuals not only to climb for long durations of time but that they are also required to climb with different loads attached to them via tool bags. Load carriage takes place across many different occupations with historic literature suggesting that 18th century foot soldiers seldom carried more than 15 kg (Knapik, Reynolds and Harman 2004). More recently this figure has risen in United States soldiers with estimated loads exceeding 50 kg due to the needs to minimise auxiliary support and development in load carriage equipment and physical training (Knapik, Reynolds and Harman 2004). This has led to the development of different load carriage systems and research to identify the effect of load carriage systems on different tasks and the human body (Birrell and Haslam 2010; Fallowfield et al. 2012; Simpson, Munro and Steele 2012; Scales 2017; Angelini et al. 2018; Looney et al. 2018). When investigating the physical demands of an activity relative to ladder climbing in renewable energy, it is necessary to conduct research which reflects the real world demands of the industry. This has been seen in research conducted Bilzon et al. (2001) and Milligan (2013) when investigating the demands of conducting fire fighting tasks and for those working in the oil and gas sector. Tipton, Milligan and Reilly (2013) highlight three areas to be considered during the analysis of tasks: equipment, load movement and environment. Such specific considerations are fundamental when considering the wind energy industry, because as has been demonstrated in chapter five, vertical ladder climbing is biomechanically different from pitched ladder climbing. As a result, for research to be relatable, and have ecological validity, ladders need to be vertical.

The results of chapter three highlighted that as well as climbing with external loads, wind turbine engineers were required to climb wind turbines within a restricted space. Anecdotal evidence from chapter six highlighted that climbing within the confines of a wind turbine can lead to an alteration in climbing technique to reduce the strain placed on the body. Although there has been analysis of climbing biomechanics undertaken on pitched ladders (Dewar 1977; McIntyre 1983; Hakkinen, Pesonen and Rajamaki 1988) and vertical ladders (Bloswick and Chaffin 1990; Hammer and Schmalz 1992; Pliner et al. 2014), all of this has been conducted on short ladders with a focus on either preferred gait or risk of slippage. Furthermore, as highlighted in chapter four, pitched ladders have a different physiological demand to that of vertical ladders, it is unsurprising that self-selected techniques differ between pitched and vertical ladder climbing (Hammer and Schmalz 1992). This illustrates the unique nature of the wind turbine technicians' role. Another unknown is understanding the effect of space restriction because this might impact adversely on larger individuals as well as when individuals climb smaller or tapered wind turbine tower designs. To date there is a gap in understanding the effect of space on ladder climbing technique and climbing technique generally in extended ladders.

With reference to load carriage, only one study (Kamon, Metz and Pandolf 1972) has investigated ladder ergometer climbing with loads. However, this study cannot be generalised to the renewables sector as the loads were on the ankles and wrists rather than attached to a full body harness, which suggests the study would not be ecologically valid. Further to this (as outlined in chapter five) the use of a pitched ladder ergometer in their study leads to a reduced demand compared to that of vertical ladder climbing. Therefore, there is currently no ecologically valid vertical ladder climbing research relating to the wind energy industry.

As has been previously been highlighted in chapter three the external loads used by those climbing wind turbines can be up to 15 kg in a tool bag and the time taken to climb a wind turbine could be in excess of 15 minutes. Taken together, despite key research which underpins a range of industrial applications, there is no research which has attempted to ascertain the effect of loading when climbing vertically. This is a key question which requires answering when aiming to understand the demands expected of ladder climbing relating to the wind energy industry.

Therefore, based on the results of chapter three and the knowledge gap stated above, this study aimed to investigate the effect of external load carriage on vertical ladder ergometer climbing both physiological and biomechanically. It was hypothesised that any increase in external load would lead to an increase in physiological measures compared to that of no load. This study also aimed to ascertain whether different load magnitudes affected the physiological responses differently. An additional objective was to generate an understanding whether gender or body size influences load carriage.

A secondary aim of this study was to investigate whether the biomechanics of ladder climbing alter in relation to the space requirement for climbing. It was hypothesised that individuals with a larger stature would require more space for climbing.

7.2 Method

7.2.1 Study Design and Justification

The study was a two-session study with session one being a within session crossover design consisting of three different loading conditions. The order of the loading conditions was randomised

(Randomizer.org 2016). The second session was a cross sectional design consisting of four space conditions with each reducing in distance. Prior to undertaking the testing session, participants completed a familiarisation session which took place a minimum of 48 hours prior to the testing session and a minimum of 48 hours between the two testing sessions. Ethics permission for this study (SHS/16/11) was granted by the School of Health Sciences Research Review Group at Robert Gordon University, Aberdeen.

7.2.2 Participants

A sample size of 40 was calculated based on the results of Phillips et al (2016) study on treadmill walking with a load. The results of this were then used alongside Cohen's (1992) sample size table to estimate the appropriate number of participants. 40 healthy adult participants (20 male and 20 female) were recruited via an internet advertising website (Gumtree), word of mouth and emails to students and staff at the Robert Gordon University. Participants were emailed a copy of the participant information sheet (Appendix X) prior to the study and any questions answered in person or email before a familiarisation session was arranged. The demographics for all participants are summarised in table 7.1. All participants provided informed consent and answered no to the questions on health conditions for exclusion (See appendix XI). Participants were also free to withdraw from the study at any point without a reason.

Table 7.1 Physical and demographic data of participants

Gender	Age (years)	Stature (cm)	Mass (kg)	Fat Free Mass (%)
Female (n=20)	20.8 (±2.6)	167.9 (±6.3)	66.1 (±8.4)	73.83 (±5.6)
Male (n=20)	21.5 (±5.0)	176.4 (±6.7)	72.5 (±9.4)	85.82 (±6.6)

Values are mean and SD, fat free mass (FFM) derived from Bodpod (See 7.2.5.2)

7.2.3 Protocol Development

This study was based on findings of chapter three which highlighted that wind turbine technicians climbed with external loads up to 15 kg. Pilot testing took place to determine the suitability of using both 5 kg and 15 kg external loads with non-habitual ladder climbers, and to determine the most appropriate climbing external loads. However, not all individuals were able to complete the 15 kg condition, therefore based on several factors including safety, the need to maximise the number of participants completing and the need to maintain a submaximal testing condition a 10 kg external load was deemed more appropriate. The use of 10 kg is still within the range provided by the respondents of the survey and using both 5 kg and 10 kg also allowed for profiling the effect of different external loads. Because the aim of the study was to ascertain the effect of external load, it was deemed that only one speed would be used for testing as to not conflate the change in results with other factors. By including a variation in the speed this would have increased the number of trials required by the participants and increased their burden which would have increased the likelihood of fatigue impacting the results. Further to this, an increased sample size would have been necessary which would have been difficult to achieve. This speed (7.58 m per min) is in line with that used by Milligan (2013) for short ladder climbing and Barron et al. (2016) for longer vertical climbing. Furthermore, the use of a slower speed was used to improve the reliability of oxygen consumption based on the work in chapter 4 showing greater absolute reliability at slower speeds.

The space requirements for the second testing session were developed based on the schematic drawings of a 30 m wind turbine (Appendix XII). The turbine is divided into three sections and the space used in the study was based on the distance from the front of the ladder to the inner wall of the turbine tower. The mean distance for each of the three for the sections were: 0.88, 1.03 and 1.23 m. These distances were measured on the ground from the front of the turbine to a moveable wall which was used to restrict the space. This wall was rigidly constrained to remain vertical.

Further to this, the piloting of different markers, as shown in figure 7.1, was conducted in order to assess the most consistently tracked marker as well as to establish marker positioning. Marker B the reflective marker, showed higher contrast and improved marker tracking by comparison to the contrasting Marker A. It was also observed that using larger (14 mm v 9 mm) markers (Vicon) for the shoulder increased the consistency of visibility of the shoulder marker as the 9 mm was obscured by the movement of the shoulder.

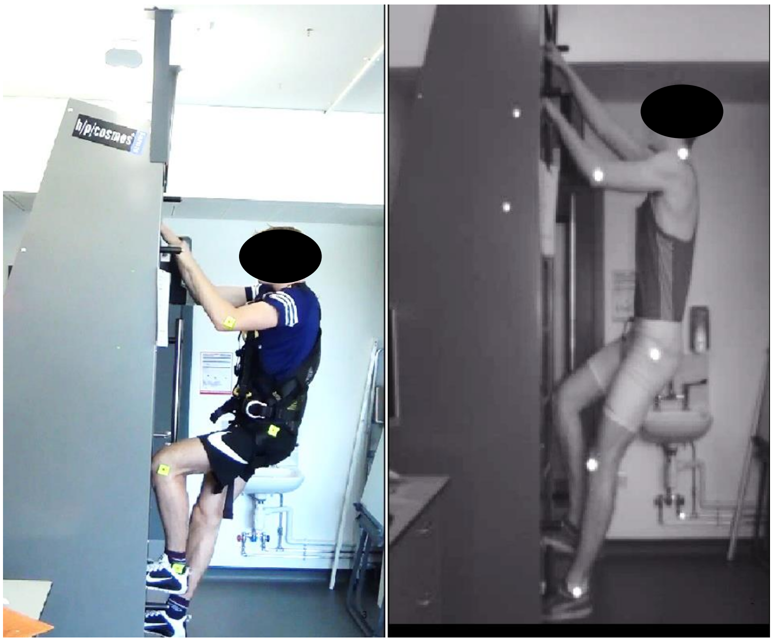

Figure 7.1 Paper (Marker A) and Reflective (Marker B) pilot testing

7.2.4 Experimental Protocol

7.2.4.1 Familiarisation session

Participants were provided a participant information sheet and had the opportunity to have any questions answered before checking whether or not they had any of the health conditions which would exclude them from participating (See Appendix X). The participants then provided informed consent before changing into sports clothing. Participants were then seated for approximately 5 minutes before having their blood pressure measured (Omron HEM-907, Omron, Kyoto Japan) to check the systolic value did not exceed 140 mmhg or 90 mmhg for the diastolic value. If the reading did not exceed these values, then the participant was deemed healthy to take part in the study. At this point participants were shown how to use the ladder ergometer and then given an opportunity to familiarise themselves with it. The ladder ergometer was slowly accelerated up to 7.58 m per minute before participants climbed for between 3 to 5 minutes depending on their level of comfort. Participants then had a 5-minute recovery before climbing for another 5 minutes at 7.58 m per min to simulate testing conditions. After this the main test session was arranged and the instructions for the testing session given.

7.2.4.2 Testing session one-External Load Carriage

Prior to the arrival of a participant a high-speed video camera (Quintic, Sutton Coldfield, United Kingdom) was set up on a tripod 3.5 m from the left-hand side of the ladder ergometer at approximately 2.5 m above the floor to capture a sagittal plane view of both participant and the ladder ergometer. Quintic Biomechanics V29 (Quintic, Sutton Coldfield, United Kingdom) was used for all video capture with the camera recording rate set to 150 frames per second for all participants. The position of the tripod and camera was marked in the lab to ensure consistency across all participants.

Before every testing session the Bodpod (Cosmed SRL, Rome Italy) had the scale calibrated before the arrival of participants. This included a calibration of the weighing scale and the volume of the Bodpod. Participants were asked to change into tight fitting shorts, swimming costume or swimming trunks as well as to remove watches and jewellery before having their stature measured in accordance with the ISAK protocol (Stewart et al. 2011). This value was then used during the set up and calibration of the Bodpod. During the setup of the Bodpod the participant was weighed and their body mass directly input into the Bodpod system. The participants were weighed in the appropriate clothing for the Bodpod including a lycra cap. The participants then undertook two Bodpod measurements, following the standard procedure, and a third if the system deemed it necessary. This was due to inconsistencies within the measured volumes exceeding the manufacturers tolerances. Fat mass was calculated automatically by converting the density via the Siri equation (Siri 1956) by the Bodpod system and then % fat and % FFM were calculated retrospectively.

Once this was completed the participants changed into sports clothing (shorts and t-shirt or vest top) and fitted with a Polar H1 heart rate monitor strap (Polar Fi, Kempele Finland). Participants then completed a five-minute warm up at 7.0 m per minute before being fitted with the Cosmed K4 B^2 (Cosmed SRL, Rome Italy) which was calibrated for each participant following the protocol outlined in appendix VI. Participants were then fitted with a size appropriate Petzl Volt wind harness (Petzl, Crolles, France) and 5 markers which were positioned at the shoulder and at the approximate lateral aspects of the joint centres of the elbow, hip, knee and ankle. All markers were placed on the left side of the body. The shoulder marker was placed posterior and inferior of the acromiale, which was to account for the movement of the arm which can obscure the landmark from the video camera if placed on the joint centre. The corresponding approximate joint centres for the other landmarks were the most central point of the radiale landmark site; most central and lateral point of the greater trochanter; the most lateral point approximately between the lateral femoral epicondyle and the tibiale laterale height site; and the most lateral and central point of the lateral malleolus. At this point the participants were told the randomised order of the loads they would be climbing with.

Participants then aimed to complete three five-minute bouts of ladder climbing at 7.58 m per minute with 5 minutes recovery between the bouts. The three corresponding loads to be climbed with were no load, 5 kg and 10 kg. These loads were made up using sand and weighed in sealed plastic bags before being placed in Petzl large and small climbing bags (Petzl, Crolles France) (Figure 7.2).

Figure 7.2. Petzl Climbing Bags

The participants climbed onto the ladder ergometer before the appropriate load was attached to the harness at the equipment attachment point via a karabiner as shown in Figure 7.3. Participants were given 3 seconds countdown before the ladder ergometer was accelerated up to the test speed.

During the test participants were encouraged and told “to do as much as you can manage”. If the participants were unable to complete the whole five-minute bout at any of the three loads they were then ineligible to complete the rest of the test. $\dot{V}O_2$ consumption and heart rate (HR) were monitored throughout the testing session and the data averaged over the last minute of each stage. Rating of perceived exertion (RPE) was recorded at the end of each stage using the 10-point Borg RPE scale (Borg 1980). These measures, as per chapter four to six, were deemed most appropriate for relating to the medical fitness standard and providing as base understanding of the effect of external loading on vertical ladder ergometer climbing. Whilst, the addition of EMG would have added to this study at the time of study the impact on forearm fatigue was not known and it’s importance currently not deemed central to the thesis outcomes when relating to the initial querying of the medical fitness document. The video was recorded for approximately three to four minutes of the climbing bout. Filming commenced after climbing was underway and terminated before volitional fatigue or the end of the test. This enabled the researcher to focus on spotting the participant and assist them dismounting the ladder ergometer.

Figure 7.3. Example of external climbing load attached

7.2.4.3 Testing Session two - Space Restriction

Upon arrival participants were asked whether their health status had changed since the last testing session and if they had any medical conditions which would exclude them from partaking in the testing session. Participants had their sitting height, stature and mass measured in accordance with ISAK protocol (Stewart et al. 2011). They also had 2 heights, 3 segmental lengths and 2 breadths measured also in accordance with ISAK protocols (Appendix XIII) (Stewart et al., 2011): sitting height, biacromial breadth, biiliocristal breadth, acromiale-radiale length, radiale-stylion length, trochanterion-tibiale laterale length and tibiale laterale height.

Participants were then be fitted with a Polar H1 heart rate monitor strap (Polar Fi, Kempele, Finland) before completing a 5 minute warm up climbing at a rate of 7.58 m per minute. Participants were fitted with a Petzl Volt Wind harness (Petzl, Crolles, France) and then fitted with the markers (See 7.2.4.2). The video capture system was also identical to that of session one (See 7.2.4.2)

Participants completed four 5-minute bouts of climbing at 7.58 m per minute with 5 minutes recovery between each. Near the end of each bout participants were asked for their RPE in the same manner as the first testing session. Mean HR was recorded for the final minute. The next 3 exercise bouts were altered to confine the space behind the participant, the aim of this will be to replicate climbing in a wind turbine. Participants climbed at the same rate with a solid wall behind them(Figure 7.4). The distance from the ladder to the screen for the exercise bouts will be 0.88, 1.03 and 1.23 m.

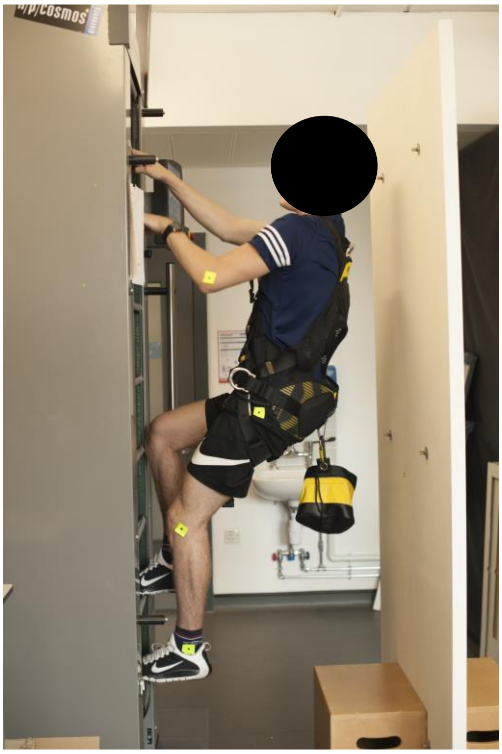

Figure 7.4 Example of space restricted climbing

7.2.5 Statistical Analysis

7.2.5.1 Statistical analysis of external load

All statistical analysis was conducted using SPSS V.21 (IBM, Armonk, USA). The HR and $\dot{V}O_2$ data were assessed for normality within each loading condition and were also assessed with gender as a factor. A repeated measures ANOVA was run to assess the effect of load on $\dot{V}O_2$ and HR with a Bonferroni post hoc test to reduce pairwise error. Effect sizes for the effect of the load on $\dot{V}O_2$ and HR between conditions were calculated using Cohen's d and interpreted using guidelines set out by Winter, Abt and Nevill (2014). A factorial one way repeated measures ANOVA was used to assess the change in RPE with gender being used as a factor. A one way repeated measures ANOVA was conducted in order to assess the change in unloaded and loaded left hand time and total cycle time for all three loading conditions (See 7.2.6 for description).

7.2.5.2 Statistical analysis of space

All space analysis was conducted using SPSS (IBM, Armonk, USA) and Quintic Biomechanics V29 (Quintic, Sutton Coldfield, United Kingdom). HR was assessed for normality using the Komologrov-Smirnov test (Field 2012). A repeated measures ANOVA was used to ascertain whether there was used to analysis the change in the distance from the ladder to the most posterior point of the body.

7.2.6 Biomechanical analysis of technique

Initially 10 male and 10 female sets of videos were randomly selected for conducting a notational analysis and for assessing the principles of movement of ladder climbing both with and without an external load. From these a critical movement analysis was undertaken by observation. The results of this were used to create a movement framework (Table 7.2) which was used for systematically observing each video. The movement framework was also shaped by the work on Dewar (1977) and Häkkinen Häkkinen, Pesonen, Rajamäki(1988) which informed the categories of gait choice. These publications initially highlighted 2 and 4 beat climbing gait as well as diagonal and lateral gait. The definitions of lateral and diagonal technique were used as guidance when conducting the analysis of movement. Based on the outcomes of the framework a quantitative analysis was undertaken to assess joint angles and proximity to the ladder. Lees (2002) suggested that instead of creating a framework based on movement principles and phase or critical analysis, that a logical approach could be used. This method bases a qualitative framework solely on the published literature, for example the work conducted by Dewar (1977) and Häkkinen, Pesonen, Rajamäki (1988) who analysed the ladder climbing gait. However, these studies differ from the present study which involves the ladder being vertical and not pitched. This suggests that the analysis conducted on vertical ladders by Pliner et al. (2014) could have been used as a basis for establishing a framework although the length of the ladder was different from the equivalent climbed in the present study. Further to this, the inclusion of an external load and the use of a ladder ergometer as opposed to a fixed ladder, could potentially alter technique. A uniqueness of the ladder ergometer, as observed in chapter four, the timing and flight phase of climbing a ladder ergometer can lead to different adaptations and individuals could potentially show different climbing traits compared to that on a fixed ladder. Therefore, a tailored analytical framework was deemed more appropriate than developing one from current literature. However, as outlined previously, the definitions of gait and technique were used to aid in the classification of climbing technique. One cycle was defined as the right hand grasped a rung through to this moment again.

A comparison of the loaded and unloaded time from the left hand as well as total hand cycle time when climbing was conducted to assess the effect of load on climbing biomechanics. This was measured when the left hand departed the rung until reconnecting with another rung (Unloaded time). The time period from the first contact with the rung until the departing of the left hand was defined as the loaded time with total cycle time being the addition of both times.

Table 7.2. Movement Framework Classifications

Defined Terms			
Beat Technique	2 Beat Lateral	4 Beat Diagonal	Undefined
Hand Pronation	Overhand	Underhand	Mixed Grip
Hand use at all times	Yes	No	
Using the ladder for recovery	Yes	No	

7.3 Results

7.3.1 Statistical external loading Results

All 20 males completed all of the loading conditions, however, there was the unexpected loss of one bout of data for one participant. Within the female sub-set not all participants were able to complete all loads with the breakdown on participants completing each different condition shown in table 7.3. The exact withdrawal rates for individual loads were not able to be calculated.

Table. 7.3 Female completions of the loading conditions

No bouts completed	No load only	Only 5 kg	No load and 5 kg	No load and 10 kg	5 kg and 10 kg	All 3 loads
2	2	3	2	2	1	8

As a complete dataset, without gender as a factor, all $\dot{V}O_2$ values were normally distributed but the HR values at no load and 5 kg were not normally distributed ($p < 0.05$). When gender was used as a factor for assessing normality the data were normally distributed for all loads for both $\dot{V}O_2$ and HR. The mean values for HR and $\dot{V}O_2$ at all loads are shown in table 5.4 including the pooled means and within each gender.

Table 7.4. Mean $\dot{V}O_2$ and HR data

	No Load		5 kg		10 kg	
	$\dot{V}O_2$	HR	$\dot{V}O_2$	HR	$\dot{V}O_2$	HR
Female (n= 18)	36.29	173.0	38.22	176.0	40.03	179.9
	(4.12)	(16.8)	(4.10)	(16.4)	(4.66)	(18.3)
Male (n =20)	36.41	154.3	37.91	160.2	40.18	164.8
	(3.57)	(23.9)	(3.18)	(20.0)	(3.46)	(17.1)
Mean (n= 38)	36.36	162.0	38.04	167.0	40.12	170.2
	(3.74)	(23.0)	(3.53)	(20.2)	(3.88)	(19.1)

The results of the repeated measures ANOVA suggested there was no significant interaction effect between loading condition and gender ($N = 26$) ($p > 0.05$), therefore the data were analysed as a pooled data set. There was a significant main effect for load on $\dot{V}O_2$ with further analysis showing a significant increase in $\dot{V}O_2$ between no load and 5 kg, no load and 10 kg and 5 kg and 10 kg. The analysis of HR ($N = 28$) showed no interaction effect between HR response and load.

The median RPE data are presented below in table 7.5. There was no interaction effect for RPE and gender however, a there was a significant difference between the male and female and female RPE's. The results showed that there was an increase in in RPE in the complete dataset as the load increases however, in females the median RPE was the same for both 5 and 10 kg. Whereas, the male data showed a continuing rise in RPE.

Table 7.5. Median RPE data

	Loading Condition		
	No Load	5 kg	10 kg
Female	5.0	7.0	7.0
Male	3.5	5.0	6.0
Mean	4.0	5.0	7.0

7.3.2 External loading biomechanical analysis of technique results

The data for males and females were pooled because a one way ANOVA showed no significant differences in technique choice between the groups. The percentage breakdown of each technique within each of the loading conditions is shown in table 7.6

Table 7.6. Predominant gait prevalence

	Unloaded (%) N = 33	5 kg (%) (N=37)	10 kg (%) (N = 37)
Undefined	12.1	13.5	16.2
2 beat diagonal gait	18.2	5.4	10.8
4 beat diagonal gait	3.0	2.7	0.0
2 beat lateral gait	30.3	29.7	24.3
4 beat lateral gait	12.1	21.6	24.3
2 beat undefined gait	3.0	2.7	0.0
4 beat undefined gait	21.2	18.9	18.9
Undefined beat lateral gait	0.0	2.7	5.4
Undefined beat diagonal gait	0.0	2.7	0.0

A repeated measure ANOVA showed no significant change in technique across the three conditions by those who completed all three test conditions. Of those who completed all three loads 35% of those maintained the same climbing technique throughout all three test conditions.

Participants were seen to use a different in hand grip orientations and the results for the three loading conditions are shown in table 7.7.

Table 7.7 Breakdown of predominant hand grip orientation

	Unloaded (%) N = 32	5 kg (%) (N=37)	10 kg (%) (N = 37)
Overhand	51.5	56.8	64.9
Underhand	15.2	10.8	8.1
Mixed	33.3	32.4	27.0

A minority of participants did not use their hands when climbing in each of the three loading conditions. This meant that some participants used the elbow and forearm to stabilise themselves on the inside of the ladder rungs. The 5 kg condition had the lowest number of participants not using their hands (5.6%) followed by 10 kg (8.3%) and the no loading condition had the highest representation at 12.1%, The use of a ladder ergometer can allow participants to recover during the exercise bouts. It was seen that 22.9% of participants used the ladder for recovery during the unloaded bout, 18.2% during the 5 kg bout and 23.5% during the 10 kg bout.

7.3.3 Space Constraint results

All male participants completed the four conditions however, five female participants did not return for the second testing session. Therefore only 35 sets of data were available for analysis. There was no interaction effect present for space requirement and gender. A repeated measures ANOVA showed that there was not a significant main effect for the change for the space required between the space restricted conditions. Further contrast analysis showed that there was a significant difference for the space required related to gender. Pairwise analysis demonstrated significant differences in the space requirement for climbing between the genders in each restricted condition (Table 7.8). The mean values for the space requirement are shown in table 7.8.

Table 7.8 Mean space requirement

	Horizontal space required (meters)			
	Unrestricted	1.23 m	1.03 m	0.88 m
Female (N = 15)	0.52 (± 0.08)	0.53 (± 0.07)	0.53 (± 0.07)	0.52 (± 0.07)
Male (N = 20)	0.65 (± 0.08)	0.62 (± 0.06)	0.63 (± 0.07)	0.62 (± 0.07)
Mean (N = 35)	0.57 (± 0.09)	0.57 (± 0.08)	0.57 (± 0.08)	0.56 (± 0.08)

The results for HR and RPE were also pooled with the mean HR values and the median RPE values shown below in table 7.9. No interaction effect was observed for HR between gender and space requirement. A repeated measures ANOVA showed main effect for the effect of space on HR with each condition significantly different from every other except for 1.03 m v. 1.23 m. The conditions with the larger space or unrestricted condition showed a lower HR than the more restricted conditions in a pairwise comparison (Table 7.9).

Table 7.9 Mean HR and median RPE values for space restricted study

	Unrestricted		1.23 m		1.03 m		0.88 m	
	RPE	HR (bpm)	RPE	HR (bpm)	RPE	HR (bpm)	RPE	HR (bpm)
Female (n= 15)	4	158.75 (17.9)	4.5	161.8 (18.5)	5	164.4 (17.9)	5	166.3 (21.0)
Male (n =20)	3	143.2 (20.0)	3	146.6 (20.3)	3	149.1 (21.4)	4	148.5 (17.9)
Mean (n= 38)	4	150.5 (20.3)	4	153.7 (20.7)	4	156.3 (21.0)	4.5	156.9 (21.3)

Pearsons' correlation coefficient showed significant ($p < 0.05$) correlation for stature with horizontal space requirement across all four conditions with R^2 ranging from 0.45 to 0.24. The same trend was recognised in sitting height with R^2 ranging from 0.36 to 0.17. Whilst many other significant correlations were observed however, none exceeded that of $r = 0.6$.

7.4 Discussion

7.4.1 Response to climbing with an external load

This study highlighted that climbing with either 5 kg or 10 kg on top of the mass of personal protective equipment (PPE) significantly increased $\dot{V}O_2$ of vertical ladder ergometer climbing. This is a significant finding as it highlights that individuals who undertake loaded climbing as part of their job requirement are put under greater physiological strain than those who don't. The changes observed were a 4.6% increase in $\dot{V}O_2$ from no load to 5 kg and 10.3% increase from no load to 10 kg, these were classified as small (0.40) and a large effect (0.92), respectively. These values do not align with RPE which showed a 1.0 and 2.0 increase in units between the stages suggesting the perception of intensity was greater than the physiological response. Furthermore, the increase in RPE at the increased intensity demand could suggest an exponential perceptual response which has previously been reported (Borg 1990). Although more data would be required to confirm this hypothesis. It should be noted that the significant difference in response by male and female participants highlights the impact that including a 5 kg load led to. This included a median RPE response of 7.0 in the female population with the male population showing a 5.0 response. Whilst no maximal testing took place the RPE values were reported suggested that individuals were working “very hard” with median values of 7.0 for both male and females at the 10 kg condition. This study is the first to specifically investigate the effect of external loading on vertical ladder climbing relating to wind energy using industry relevant positions with Kamon, Metz and Pandolf (1972) having conducted similar research but using the different conditions (pitched ladder) but on the ankles and/or wrists. However, based on the findings in chapter five it would not be appropriate to conduct comparisons between the studies due to the differing pitches used (90° v. 80°) and it has been ascertained that a lower pitch has a lower physiological demand. Blacker et al. (2009) found that treadmill walking with 25 kg increased $\dot{V}O_2$ by 41 ± 17% higher compared to unloaded after five minutes and 19 ± 17% after two hours. The greater increase in difference is hypothesised to be due to cardiovascular drift due to the increased demand of loaded walking (Blacker et al. 2009). Whilst this highlights that load carriage can incur a great energetic demand compared to unloaded it should be highlight that this study used a backpack for load carriage. The type of load carriage system and its relationship to the centre of mass can affect the kinetic response to a fixed load (Birrell and Haslam 2010). Although this load carriage system differs from that of a climbing bag as used in this study. The main differences are that the backpack sits as part of the trunk and is fixed in place whereas, by comparison the climbing bag sits outside the body and often the base of support (Figure 7.5) and can generate its own momentum by swinging. This is then anticipated to impact on climbing biomechanics and it was observed that at heavier loads some participants were rotating with the swing of the external load. It would be possible that this could impact on the force through the hands to maintain balance and increase localised fatigue which was reported by participants.

It is necessary to fully understand (e.g. comfort, physiologically, biomechanics and RPE) how external load carriage affects different individuals’ response to ladder climbing. This has been outlined in previous chapters with differing perceptual responses to different stimuli (Climb assist, increased climbing speed and pitch) and it is important to understand the impact of different factors on physiology and perceptual response. The use of RPE could be used to provide instruction on how to adjust climbing speed based on the inclusion or exclusion of load or climb assist if it were possible to reliably generate research to understand the link between RPE and physiological response to ladder climbing. This is important in order to generate a complete picture of the response to external loading and other factors prior to a change in industry regulations. Dzialos et al. (1987) highlighted that isometric hamstring strength is one of the key predictors of performance during a load bearing marching to differentiate fast and slow march times. Furthermore Rayson et al. (2000) highlighted that muscular strength is a better predictor of load bearing task performance compared to muscular endurance. No strength assessments were made in the current study, and therefore no direct comparison is possible. In respect of the relationship between body mass and HR or $\dot{V}O_2$, contrary to previous studies, no correlation was found. However, no such measures were taken in this study but body mass did not correlate with either HR or $\dot{V}O_2$ response to the climbing loads. This response differs from other studies however, this may be due to the more physically demanding nature of ladder climbing by comparison to other studies which used walking. With respect to ladder climbing a larger body mass may not be beneficial as this may be ballast mass which would not positively contribute to aiding move the centre of mass (COM). If strength in general is considered one of the strongest indictors of performance, then that could potentially be highlighted itself as FFM. Whilst the two-compartment model of body composition could be used to indicate muscle mass it should noted that the FFM is also made up of protein, minerals, glycogen and water. In this study FFM significantly ($p < 0.05$) negatively correlated with the all three loading conditions for absolute HR and at 10 kg for $\dot{V}O_2$ with correlations all ranged from $r = -0.50$ to $r = -0.60$. This therefore suggests that the absolute FFM, and therefore potentially muscle mass, is an important factor when understanding how an individual will respond to an external load. As FFM increases the oxygen consumption decreases, in the 10 kg loading condition. The sample population in general for this study were athletic individuals and this may manifest itself in suggesting that those with lower fat mass were fitter. It could be assumed that these fitter individuals were working relatively easier than those with lower FFM and the fitter individuals would be working at a lower percentage of their $\dot{V}O_2$ max. Subsequently, it is then thought that the less fit individuals were working near to their $\dot{V}O_2$ max when undertaking the 10 kg condition. However, without ascertaining how close to their maximum participants were working it could be difficult to understand the interaction of FFM, external loading and oxygen consumption. However, RPE in the 10 kg loading condition significantly negatively correlated with FFM ($r = 0.41$) suggesting those with greater FFM perceived the external load to be easier. This highlights a requirement for more research to be conducted to understand the relationships of external load, body composition and energetic cost of climbing.

It must be recognised that the two-compartment model used by the bodpod uses does not analyse muscle mass and produce results. However, it was historically viewed as a gold standard although this is no longer the case, and predictions may differ from other methods if the density of the fat-free mass or the proportion of its constituents vary, therefore this explanation is currently best fit (Ackland et al. 2012). In order to understand fully the relationship between body composition and vertical ladder climbing it would be necessary to utilise a different method of body composition analysis, such as Dual-energy X-ray absorptiometry to gain a clearer understanding of the interaction of muscle mass and vertical ladder climbing. However, the use of the Bodpod provides an insight to the relationship between body composition and vertical ladder climbing which has not been reported in this context.

7.4.2 Relative Loading

The topic of relative load and the effect of external loading on biomechanics and physiology has been studied when related to the walking with backpacks as well as in the armed forces. However, to date no research has been conducted on load carriage in ladder climbing or specifically related to the wind energy industry with appropriate PPE. This study had participants undertake ladder climbing with a climbing harness and appropriately sized tool bag containing either a 5 kg or 10 kg external load which led to complete PPE and load totals of 7.27 kg and 12.34 kg respectively. Whilst the relative additional load (Table 7.10) did not correlate significantly with $\dot{V}O_2$ or HR the addition of such load should be carefully considered in the industry and the long-term implications. Currently research within other fields has shown loading can increase musculoskeletal injury risk, even load distribution is more beneficial, the closer a load is to the COM the smaller the impact and that load carriage can impact on neuromuscular function and strength for 48 hours (Lloyd and Cooke, 2000; Blacker et al. 2010). Further to this, anecdotal evidence was that the maximum height to be climbed in one working day was 240 m which equating to three 80 m wind turbines. Based on the results of this study the energetic cost of climbing 240 m would significantly differ depending on the load used when climbing. If a typical individual was to climb with 10 kg this incur an approximate increase in $\dot{V}O_2$ of 10% this could have an impact on say accrued fatigue, recovery time and subsequent task performance. A review by Drain et al. (2016) highlighted that increasing the relative task intensity (% $\dot{V}O_2$) has a reduction on the acceptable work duration. It is not possible to estimate % $\dot{V}O_2$ however, with 32.5% of the sample reporting RPE values of 8 or greater at 10 kg it could be assumed they were working near maximally. Such increases in external load on an already demanding occupation should be carefully considered as this could have longer term implications on work durations if those in the industry work near maximally. Based on the work in chapter three which demonstrated 59% of participants climbed wind turbines four, five or six days per week and climb with typically 17.0% in males or 19.5% in females of body mass (Table 7.10) attached to their harness this could lead to performance decrements if the recovery time does not take account of this extra burden. Therefore, a longer term understanding of the effect of external loading is necessary because as this study demonstrated that an acute bout of loading significantly increased the physiological response to vertical ladder ergometer climbing. Therefore, based on the work of Drain et al. (2016), there is a need to understand the impact of load carriage on acceptable working limits as this could be a crucial factor in determining acceptable work durations.

Table 7.10. Relative load of carried weight and PPE in relation to body weight

	Mean % (± S.D)	Minimum %	Maximum %
No Load	3.1 (0.5)	2.1	4.1
5 kg	10.7 (1.6)	7.1	14.2
10 kg	18.2 (2.7)	12.0	24.1
Industry No load	10.0 (1.5)	6.6	13.3
Industry 5 kg	17.6 (2.6)	11.7	23.3
Industry 10 kg	25.1 (3.7)	16.6	33.2

Industry includes the addition of PPE where the mass was measured during the study in chapter five

The values quoted above were based on this study's use of 10 kg however, the clothing worn was not the same as worn by those working on wind turbines. The lower three rows in tables 7.10 and 7.11 are estimated wind turbine technician loads based on data from chapter 4 with a participant being weighed in full PPE which was 6.8 kg. This provides an insight into more relevant total loads and how the impact of full body coverage would alter the relative load. This study did not use the same level of required PPE, such as full body coverage, working boots, helmet and lanyards, due to the potential thermoregulation issues which could occur within a laboratory environment. Nevertheless, it would be prudent to get a more complete picture of the response to such loads as this may impact on their workload but this may have impact on the musculoskeletal system. To date there have been no specific studies which has investigated hip loading on a harness during ladder climbing making cross comparison difficult. The relative loads in this current study are lower than other industries however, the point of connection is a singular point on a full body harness rather than two straps of a backpack or a more complex load carriage system (Knapik, Reynolds & Harman 2004; Birrell and Haslam 2010). This asymmetric external loading led to a distinct pull on the harness to the side of the load which could potentially impact on biomechanics or energetic cost of climbing. Although the $\dot{V}O_2$ was not measured by Angelini et al. (2018) they found that asymmetric loading with a hose amplified the effects of acute fatigue and altered vertical and horizontal clearance heights when walking. This research lacks the specificity to be generalisable to the wind energy but, it provides an insight into the potential effect of asymmetric loading. However, this is an area that requires more research to be conducted to gain an understanding of the effect of external load carriage as well as the position and distribution of external loads.

Table 7.11 Relative load of carried weight and PPE in relation to body weight by gender

	Mean % (± S.D)		Minimum %		Maximum %	
	Male	Female	Male	Female	Male	Female
No Load	2.9 (0.4)	3.3 (0.4)	2.1	2.7	3.8	4.1
5 kg	10.0 (1.5)	11.4 (1.4)	7.1	9.2	13.1	14.2
10 kg	17.0 (2.5)	19.4 (2.3)	12.0	15.6	22.2	24.1
Industry No load	9.4 (1.4)	10.7 (1.3)	6.6	8.6	12.2	13.3
Industry 5 kg	16.5 (2.5)	18.8 (2.2)	11.7	15.1	21.6	23.3
Industry 10 kg	23.5 (3.5)	26.7 (3.2)	16.6	21.5	30.7	33.2

Industry includes the addition of PPE where the mass was measured during the study in chapter five

7.4.3 Biomechanics Discussion

7.4.3.1 Unloaded Gait Choice

This study supports the work of both Hammer and Schmalz (1992) in finding that during vertical ladder climbing the two-beat lateral gait was the most commonly used across all loading conditions. However, within unloaded conditions the findings within this study differ from that of Hammer and Schmalz (1992) who found a preference for technique in the order of: lateral two beat (~ 75%), diagonal two beat (~ 20%), lateral four beat (~ 3.5%) and then diagonal four beat (~ 1.5%). Whilst the lateral two beat was the most common in both studies, and in pitched studies (McIntyre 1983), the proportion of participants utilising the technique differs (30.3% v. ~ 75%). The difference in the prevalence between the two conditions could be due to Hammer and Schmalz (1992) using a short (3.7 m) fixed ladder and participants completing five ascents and descents instead of continually climbing for five minutes. Both studies highlight the prevailing tendencies within vertical ladder climbing and recognised that vertical ladder climbing is a fluid and complex task that can have multiple technique changes within a singular bout. This study did seek to quantify the number of times that technique changed during a bout of ladder climbing however, within a potentially infinite range, it is difficult to label climbing style in some instances, and also the point at which the predominant technique alters from one style to another of the task meant that this was not clear. However, the study did assess whether participants continually used the same technique during the period of analysis or not.

Hammer and Schmalz (1992) and many others (Dewar 1977, McIntyre 1983) have classified technique into between two (lateral and diagonal gait) and four categories which were outlined previously based on beat (two and four) and gait (lateral and diagonal). However, this study classified climbing gait into nine categories (Table 7.6) with additional five categories being formed based on the observations from the recorded videos for the loading conditions. All five of the newly defined categories are based on previously undefined techniques or gait whereas the pre-existing four were based on the work of McIntyre (1983). As mentioned in previous chapters the use of a ladder ergometer creates a subtly different stimulus than ladder climbing. The first being to gain vertical height whereas a ladder ergometer is to maintain a set position on a moving ladder. A second reason for the formation of new techniques is the duration of climbing leading individuals to adapt their technique to reduce energy demands. Such adaptations would not be observed on short ladders as the requirement for economy would not be as important. The observations on the newly defined techniques were that participants would move their hands less often than their feet which generally led to the forming of undefined beat lateral and diagonal gait categories. These were borne out of participants climbing in a manner favouring one side of the body, for lateral gait, using the two beat timing and the other side of the body using a four beat method. For the undefined beat diagonal gait the same observation was seen but with the opposite hand and foot rather than the same side. Both techniques were generally 'foot over foot', however, Dewar (1977) did recognise that asymmetric techniques may take place when climbing and that 'foot next to foot' climbing may occur. This meant that participants were placing both feet on the same rung rather than going to the rung above the one that the current foot was placed on. This was observed in some participants of this study as they could undertake a two-beat lateral technique but minimise the movement of the body and keep minimise the COM movement. It is hypothesised that by keeping the COM close to the ladder surface reduces the moment arm of inertia and therefore the force required to stabilise the body and participants felt a reduction in forearm strain. Vertical ladder climbing is a physically demanding task (Oksa et al. 2014) that has larger hand forces (Bloswick and Chaffin 1990), muscle activation at the forearms (Oksa et al. 2014) and different demands to that of pitched ladder climbing (McIntyre 1983; Barron et al 2016). Therefore, participants altering their technique in unloaded conditions to achieve an end goal of climbing for five minutes is logical. However, it should be recognised that this could also be due to fatigue and that participants are altering their technique in order to reach the end goal rather than withdraw from the study as there were unable to slow or halt their ascent. This study shows that during vertical ladder ergometer climbing the two lateral climbing gait is the most commonly used however by comparison, the dominance shown in previous work (McIntyre 1983) is not seen. It is hypothesised that the physically demanding nature of vertical ladder ergometer climbing compared to that of a short ladder leads to individuals using non-traditional techniques or adapting techniques to complete the required exercise bout.

7.4.3.2 Effect of external load on gait

The work conducted in chapter three highlighted that participants must climb in restricted spaces and this is also seen by the interior dimensions of a 30 m turbine as shown in appendix XII. It was observed that as the external load increased the relative horizontal distance of participants to the ladder increased, however, this was not measured and only observed. It is thought that the position of the external load being inferior and posterior (Figure 7.5), at times, to the COM pulls the body away from the ladder and leads to an increase in distance.

Figure 7.5 Example of 10 kg external load position

In order to have a greater understanding of the effect of external loading on climbing biomechanics a subset of eight participants who completed all three loading conditions had eight climbing cycles analysed. This was to understand whether the external load altered the unloaded and loaded hand time during the climbing with four cycles at the beginning of the bout analysed and four at the end analysed. Only left-hand analysis was conducted as only this was clearly visible from the fixed camera position. There were no significant differences between the three loading conditions for mean hand unloaded time, hand loaded time or total cycle time. Potentially the use of a one-way repeated measures ANOVA with a sample size (n = 8) may lack the sensitivity required for such analysis. However, the trends can be seen in figure 7.6 that the cycle time does decrease but this is on the basis that there is a 36% decrease in unloading time from the unloaded condition to both external loaded conditions. Small changes are seen in the mean loaded time with the mean total cycle time which elucidate a trend however, all changes would be within the expected variability with a 3.7% decrease in loaded time from no load to 5 kg and a 4.1% increase in loaded contact time from no load to 10kg. This then led to an 8.1% increase in contact time from the 5 kg to the 10 kg condition.

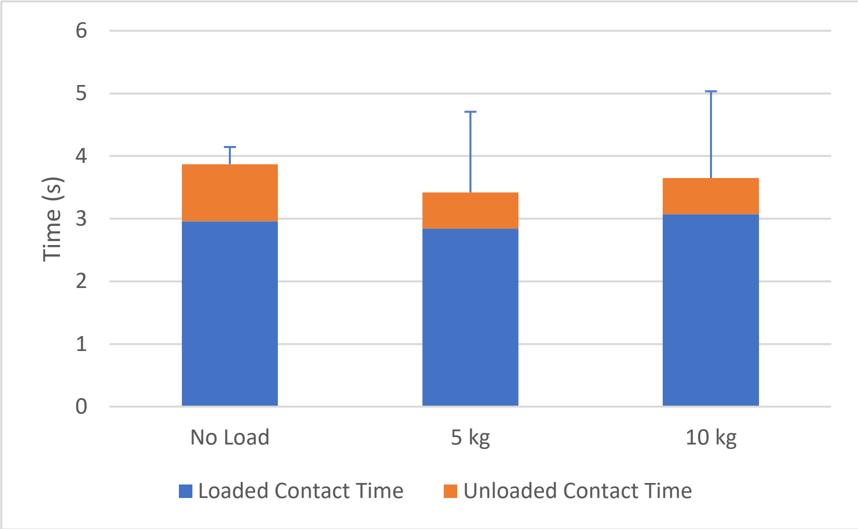

Figure 7.6 Mean climbing cycle time

Whilst statistical significance was not observed in these variables it must be recognised that a visible difference in technique was observed and that that this was exploratory by nature, and possibly affected by the momentum of the swinging weight carried. Such a change in mean unloading time reinforces the observations that once an external load was applied to the body that participants sped up the unloaded time and were more direct with their movement to reduce the non-supported time on the ladder ergometer.

7.4.3.3 Climbing Technique Adaptions

This led to participants adapting traditional techniques in order to meet the goal of maintaining their position as can be seen in the figure below. This figure shows an example of an adaptation by a participant whilst maintaining a lateral gait, as defined in the literature (McIntyre 1983) but there is a significant difference within the arm positioning which limits the body movement. This participant in this example moved their grasping hand underneath the rung below the rung they were grasping before placing their hand in a supinated position on the rung they wished to grab. By doing this the participant gained extra stability with the medial aspect of the elbow joint being rested against a rung which acted as a method of bearing some of the load when the participant was pulled backwards due to the position of the external load. Anecdotally the participant thought this reduced the load on his forearm and helped him maintain his position. Furthermore, this adaptation had an impact directly on the distance to ladder as due to the elbow joined being locked in position thus limiting the ability to adjust the distance by choice. This adaptation on the two beat lateral gait was only observed by one participant however, it outlines an example of how individuals may adapt a predefined technique whilst still remaining within the guidelines (McIntyre 1983) for a given gait and technique.

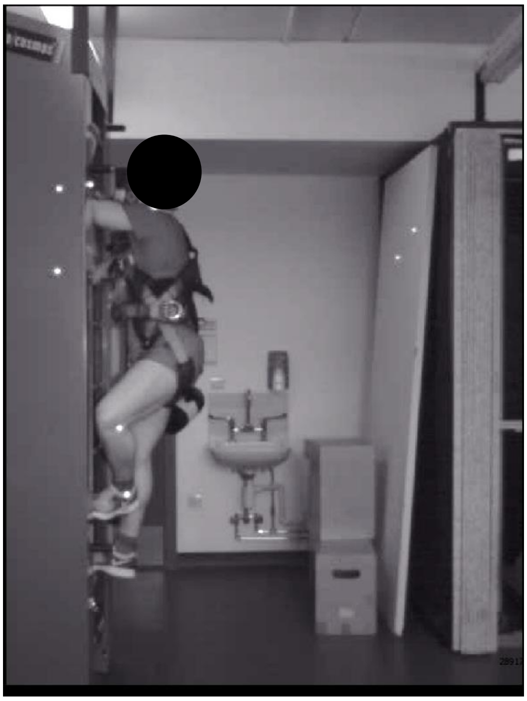

Figure 7.7 Example of adapted lateral climbing gait

Anecdotal evidence and from the video recording reported and highlight that as the external load increased the fatigue on the wrist flexors and extensors led to the feeling of impaired grip strength. This led to participants not using their hands throughout all bouts with 5.6% of participants not using their hands (Figure 7.8) for the 5 kg external load, 8.3% for 10 g and 12.1% for the no load condition.

Figure 7.8 “No hand” ladder ergometer climbing

The anecdotal evidence from the participants is in line with the work of Oksa et al. (2014) who found that the percentage of maximal electrical myography (MEMG) for the wrist extensors and flexors when ascending an electrical mast or pole were 24.0 ±1.5 %MEMG for the wrist flexors and for the extensors was 21.0 ±1.0 %MEMG. Both values exceed the suggest working guidelines of 14% MEMG for muscular activity. This study commented that the reported values were so high that they could induce local muscular fatigue which could reduce work efficiency and become an injury risk (Oksa et al. 2014). This aligns with anecdotal evidence from participants and the requirement to "shake out" their hands to help reduce the sensation of localised fatigue in the forearms. This would reinforce the work conducted by Oksa et al. (2014) and suggests that individuals are adapting their climbing technique to minimise the impact placed on their body and in particular the sensation of localised forearm fatigue. As outlined in the method sections of this chapter had the effect that forearm fatigue been known prior to this study taking place its analysis would have been included. It has the potential not only to affect work duration but also potentially act as a limiter on load carriage due to Oksa et al. (2014) highlighting that the MEMG values can exceed recommended working guidelines. This has seen two specific types of adaptations which have been outlined illustrating different methods by which participants' technique varied from the previous defined norms. Further research would be required to understand the effect of external load on muscular fatigue as this could affect the time taken to climb, the fatigue induced, the recovery required and the quality of the subsequent work undertaken.

7.4.4 The effect of space restriction

The space within a wind turbine is not infinite and the space in which an individual must climb decreases as they climb up the turbine (Appendix XII, anecdotal evidence). It was hypothesised that by restricting the space that individuals had to climb that it would significantly decrease the space in which they chose to climb. However, this was not observed in this study as there was no significant ($p < 0.05$) effect on the space in which individuals climbed relative to restriction placed upon them. Whilst the operating space they had available decreased from an unrestricted amount to 0.88 m (0.35 m decrease from the first restricted condition) the mean change in space by the participants was 0.1 m. It is of note that although technique has been shown to be variable by Dewar (1977) and in this study with only 35% of participants having used the same technique throughout the three loaded trials that mean climbing space was very consistent. This suggests that although individuals may alter their technique, they may have body position or self-selected distance from the ladder that they wish to maintain, and they alter their technique to achieve this goal. The distance from the ladder that an individual climbs appears to be in general positively correlated to their stature (R^2 range = 0.45 to 0.24) however, the correlation diminishes as the space becomes more restricted. This potentially suggests that if the space is restricted taller individuals then move closer to the ladder. However, when investigated retrospectively there was no significant correlation between the change in the horizontal space requirement and stature. It is possible that the lack of any external load allowed participants to work at more controlled level, as was seen by their RPE and HR, by comparison to loading and they could maintain a more fixed and less variable position. Although HR increased significantly throughout the space restricted trials it was hypothesised this was due to an order effect and accrued fatigue. Taken together, when climbing in a space which reduces without becoming physically restrictive, individuals horizontal space requirement for ladder climbing did not significantly change. However, it would be of interest to understand the interaction between space and loading as previous observations suggest that the use of an external load could alter the space envelope for climbing. This was not undertaken within this study due to the initial research questions aiming to ascertain the effect of load and space restriction independently. Integrating this research into this study would have increased the burden on participants and would be more appropriate once a greater understanding of the spaces required to be climbed in and the range of external loads are more defined.

7.5 Limitations

Due to the physically demanding nature of climbing with an external load, individuals were observed creating coping strategies to aid in their completion of the required tasks. An example of this was individuals climbing to the top of the ergometer and then pausing on the ladder until it reached the bottom of its climbable range. This led to them gaining momentary rest periods within the five minute duration of the exercise bout however, this may in fact reflect real world climbing where individuals require a rest during the climbing of a wind turbine. Despite pilot testing, the use of a fixed speed combined with external loading may have led to individuals' perceived or genuine inability to tolerate working strenuously, thus justifying the requirement for a micro rest period. Potentially, this could have affected the results of the study however, no noticeable change in $\dot{V}O_2$ was observed most likely due to sampling rate of the equipment and the required effort to commence moving again. It should be noted that no climbing strategy or technique advice was given at any point. It would be of interest to understand whether individuals would take rest periods or climb at a different speed if a distance goal was imposed rather than time. Nevertheless, such an aim should be considered in relation to the outcomes and objectives of the study. The aim of this study was to ascertain the effect of external loading on ladder climbing physiology and technique rather than the effect of external loading on climbing the equivalent height of a wind turbine.

It was observed that participants were rotating around the vertical axis, as seen by movement most commonly in the hips and the shoulders. This could be a result of either or all of self-selected climbing gait, the external load and the position of the external load. However, due to only one camera being used, to view the body in the sagittal plane, it was not possible to quantify either the abduction from a natural midline during the or the amount of rotation around the vertical axis because of this. The need to operate multiple cameras simultaneously was not foreseen. This is potentially an area for future research as there may be an interaction between the position of an external load and the effect on biomechanics.

Only one participant in this study was a habitual ladder climber whilst all other participants were non-habitual ladder climbers. This may have meant that some techniques adopted by participants are not representative of what takes place in the industry or conform to guidelines of three points of contact (Health and Safety Executive 2014). This may mean that the changes in $\dot{V}O_2$ or heart rate could differ from those who climb more habitually. Further to this the participants were not required to wear full PPE or climb with safety lanyards which would have increased the additional mass. As was outlined earlier including safety harness and associated clips can weigh approximately 7 kg prior to the addition of an external load. However, there is no single PPE mandate applicable to all turbines, and as a result the actual burden of PPE is likely to vary according to the employer although minimum guidelines exist (Renewable UK 2015). Nevertheless the study was able to highlight the impact of 5 kg and 10 kg external loads which, at this time will have relevance to the industry and highlights the need for future research to quantify and justify the total weight burden (PPE + tools) faced by wind technicians.

7.6 Conclusion

The addition of load carriage to vertical ladder ergometer climbing significantly increases the physiological cost, exertion and the potential to reach a performance ceiling, which is more likely in females. This is most likely due to the higher relative mass that females carry compared to their male counterparts. The implications of this are wide ranging as it provides a strong basis to suggest that the current fitness is not fit for purpose due the mean oxygen observed in this study at low speeds exceeding that of the current fitness standard. Therefore, it would be suggested that the current prescribed fitness standard is revisited with the inclusion of external load carriage. On a broader scale the additional impact of load carriage needs to be more fully understood as it could have direct implications for the acceptable work duration. Furthermore, loading affects the chosen climbing gait and appears, anecdotally, to alter the space in which some individuals climb. However, when climbing unloaded the restriction of space does not significantly alter the space envelope in which individuals climb in. However, in order to relate this to the wind energy industry more research should be conducted with industry relevant external loads to ascertain the impact of loading on the space requirement for vertical ladder climbing. Nevertheless, this research shows the impact that an external load places on individuals and strongly suggests that the current fitness standard within the wind energy industry is not appropriate. More research is required to understand the effect of external load at industry relevant speeds to ensure an appropriate fitness standard is created and that a broad range of factors are considered during this.

8.0 Discussion

The existing literature relating to the wind energy industry was limited and lacked potential for creating a fitness standard. This was due to a lack of specificity in the research pertaining to ladder climbing to relate to the wind energy industry (Kamon 1970; Kamon and Pandolf 1972; Kamon, Metz and Pandolf 1973; Vi 2008; Milligan 2013). Until recently there was limited literature relating to the wind energy itself to begin to understand what takes place in the industry (Mette et al. 2017; Garrido et al. 2018). However, prior to the publication of those two studies the only existing documentation on what takes place in the wind energy industry was health and safety documentation or medical fitness standards (Renewable UK 2013; Renewable UK 2014). Therefore, this thesis based on the medical fitness documents (Renewable UK 2013) and communication with the industry aimed to gain a greater understanding of the industry and investigate areas of interest that could be used to contribute to a physical employment standard.

8.0.1 Key findings

Vertical ladder climbing is a unique and physically demanding that differs both physiologically, perceptually and biomechanically from pitched ladder climbing (McIntyre 1983; Barron et al. 2017). The role and demands placed on wind turbine technicians, as highlighted in chapter three, identified over 50% of wind turbine technicians climbed ladders three to five days per week and the median height of the turbines was 36 m. This was corroborated by Garrido et al. (2018) and by anecdotal evidence that also advised that there is a requirement to climb up to 80 m vertically. From this chapter it was also reported that only 25% of wind turbines contained lifts and 37.5% of participants reported climb assist system in the turbines they climb. This suggests that most participants are required to climb wind turbines, with the most common duration to climb a wind turbine reported as 16 to 30 minutes. Further to this when climbing a ladder, participants reported that they had to climb with external loads up to 15 kg. The findings from this chapter were used in corroboration with reviewed literature and industry anecdotal evidence to design the future research within this thesis.

Up to this point the existing ergonomics literature base recognised that changing the pitch of a ladder altered the biomechanics, heart rate (HR) response and the force produced at the hands and feet when ladder climbing however, the effect on oxygen consumption was unknown (Bloswick and Chaffin 1990; Hammer and Schmalz 1992; Vi 2008). The modification of a ladder ergometer from 75° to 90° demonstrated vertical ladder climbing to be significantly ($p < 0.05$) more demanding than pitched ladder climbing. This was demonstrated by a mean increase of 17.3% in $\dot{V}O_2$ at matched vertical climbing rates across three different climbing rates.

For the first time empirical evidence was produced which demonstrated that climb assist devices (Barron et al. 2017) have a significant impact on vertical ladder climbing. This research conducted with habitual ladders climbers in-situ observed a large effect (d = 1.8) in reducing the oxygen consumption of participants by a mean 22.5% which was reflected with 2.0 unit drop in RPE. As expected, this study also demonstrated that steady state ladder climbing descending was significantly ($p < 0.05$) less demanding than ascending a 30 m ladder with a 46% reduction in $\dot{V}O_2$ from 28.3 $ml.kg.min^{-1}$ to 15.3 $ml.kg.min^{-1}$.

Barron et al. (2018) observed significant increases in HR, $\dot{V}O_2$ and rating of perceived exertion (RPE). Finally, the work in chapter seven showed that the use of climbing with an external load significantly increased the demands of vertical ladder ergometer climbing. There was a significant increase in oxygen consumption (36.36 $ml.kg.min^{-1}$ v. 38.04 $ml.kg.min^{-1}$ v. 40.12 $ml.kg.min^{-1}$) between all three conditions.

Vertical ladder climbing is recognised as a highly energetic activity that involves high levels of exertion, both physiologically and perceptually, and consequently personal fitness. In summary, these studies have broad implications for recruitment, fitness testing and professional practice. However, they also bring to light the need for more research to be conducted in conjunction with the industry in order for a more complete understanding of the industry as a whole.

8.0.2 Application to Physical Employment Standards

Recent work by Peterson et al. (2016) and Tipton, Milligan and Reilly (2013) stated that when aiming to design a fitness standard that the process should be informed by evidence based on peer-reviewed research. Currently there is a dearth of ergonomic literature relating to the wind energy industry by comparison to other industries such as the fire and rescue service, coastguard and the armed forces (Rayson, Holliman and Belyavin 2000; Bilzon et al. 2001; Reilly et al. 2006; Reilly, Wooler & Tipton 2006; Fallowfield et al. 2011; Milligan 2013; Siddall et al. 2014 Blacker et al. 2015). The work in chapter three highlighted several key potential research avenues that should be pursued in order to ensure that any future fitness standard has an evidence base from which to be built or to highlight the necessity for a redevelopment of the current fitness standard (Peterson et al. 2016). The frequency and duration of ladder climbing in this study, 60% of participants climbing four, five or six days per week differed from anecdotal evidence that suggested most turbines post 2009 had lifts. The present findings are similar to that of Garrido et al. (2018) who found 60.8% of offshore wind turbine often of always face ladder climbing. This present study and the work of Garrido et al. (2018) highlight that ladder climbing takes place regularly and not just in case of emergencies or for rescues (Renewable UK 2013). Furthermore, chapter three highlighted numerous other areas that could exacerbate or reduce the fitness demands of ladder climbing as part of the role of a wind turbine technicians. These were climbing with an external load up to 15 kg, the use of climb assist and the climbing within a restricted space will alter the task and change the demands of climbing a wind turbine. To date no research had been conducted and the extent to which these affected individuals was previously unknown. The research that focussed on the physiology of ladder climbing had previously all been conducted on pitched ladders which was found to show different technique preferences (McIntyre 1983) but as the present body of work has demonstrated, this alters physiological demand. The use of a ladder ergometer showed that the change from a 75° pitch to a vertical pitch significantly increased the oxygen consumption by 17.3% and perceptual responses to ladder ergometer climbing. The implication of this is that research conducted on pitched ladders is not generalisable to the wind energy industry and that pitched ladder climbing has the potential to mislead the industry if it had previously been deemed comparable to vertical ladders. The reality for the industry is that there is little or no valid evidence which is vocationally relevant from which to construct an occupational fitness standard.

The current fitness standard outlines that an individual must be able to climb a wind turbine in the event of lift failure or when rescuing a colleague and to be safe to do that they must have a $\dot{V}O_2$ max greater than 35 $ml.kg.min^{-1}$. Chapter two highlighted that there is a dearth of literature which could be used as "normative data" to define this value (Renewable UK 2013). However, based on the research that has been conducted on pitch ladders and other industries it is thought that current value has been recycled from other industries. Nevertheless, if normative data is privately available it most likely fails to recognise the potential for load carriage and personal protective equipment (PPE) as this is not mentioned within the medical fitness documents (Renewable UK 2013). Chapter three found that of those who completed the survey only 25% had lifts and over 60% of participants climbed a wind turbine four, five or six days per week. This would suggest a greater need to understand the demands of vertical ladder climbing as it occurs frequently both on and off shore (Garrido et al. 2018). Anecdotal evidence suggests that most turbines do contain lifts although the contrast in findings could be due to the difference in the companies worked for from the sample population compared to the large company who provided the anecdotal evidence. Furthermore, a non-response bias should be considered as only one large company provided gate keeper approval. Nevertheless, whether it is for emergencies or on a regular basis there needs to be a more complete understanding of the demands of such a role and the physical strain of vertical ladder climbing. This body of work highlights that the Renewable UK (2013) prescribed value most likely underestimates the demands of vertical ladder climbing. This was anticipated due to anecdotal evidence suggesting this value was adopted based on other industries. There are numerous factors that may explain why their threshold may not be appropriate based on the work in chapters four, five and six and in conjunction with the work of Milligan (2013), Tipton and Milligan & Reilly (2013) and Peterson et al. (2016).

The published literature (Tipton, Milligan and Reilly 2013; Peterson et al. 2016) suggests that the adopting of fitness standards is inappropriate due to the differing demands of various industries and the work conducted in chapter five would reiterate this. Chapter five concluded that vertical ladders are significantly more demanding than pitched ladders which would deem the adopting of a different industry's fitness standard inappropriate (Barron et al. 2018). The change from a 75° to a 90° pitch had a large effect on oxygen consumption at all speeds (d = 1.7 – 3.3) which underlines the inappropriateness of adopting a fitness standard from industries that use pitched ladders (Barron et al. 2018). This reasoning can be a starting point for revisiting the 35 $ml.kg.min^{-1}$ guideline set by Renewable UK (2013) however, the results from chapter five and chapter six add further weight to the need to investigate this further. The unloaded condition in chapter seven and the vertical climbing conditions in chapter five all had mean $\dot{V}O_2$ values exceeding that of the current recommended standard. The current fitness guidelines do not currently prescribe a minimal or maximal climbing speed that could be used as a guide as a reasoning for their prescribed value. Such information would be necessary to understand the minimal acceptable climbing rate as to more fully understand the demands placed upon individuals. Nevertheless, at a range of vertical climbing speeds ranging from 7.58 m per minute up to 15.4 m per minute, the mean demands exceeded that of the current industry guidelines These findings support the argument that the fitness standard should undergo reform and that the climbing rate versus physical demand should be considered. This was done by Milligan (2013) and reiterates the need to engage with the industry body to ensure such details are appropriate.

It should be recognised that the sample population within this study comprised young fit adults and that may not be representative of the current industry population. Garrido et al. (2018) conducted a questionnaire in the off-shore wind sector and their demographics were 43.4% male aged between 20 -34 and 45.5% males aged between 35 – 49 with an overall study population of n = 268. These ages are considerably higher than the mean age across the studies conducted in this thesis. However, the base premise remains the same: that individuals being passed fit to climb a ladder at value up to 25% lower than the measured demands is inappropriate and unsafe. Further investigation is required to understand this as this has an impact on recruitment and welfare of individuals. It is most likely with the increased dependence on renewable energy within the UK and the rest of Europe, that the workforce will increase and most of these individuals are unlikely to be highly athletic. As a result, an understanding of the minimal acceptable speed for climbing is required to set an appropriate benchmark. On the other hand, the understanding of the minimal or maximal acceptable speed will potentially dissuade individuals from producing such an effort that requires them on a daily basis, or multiple times each day to work near maximally when climbing a ladder. It is not unreasonable to assume that such efforts could only increase the chances of adverse events occurring. Therefore, this work would encourage the renewing or redeveloping of the medial fitness standards.

8.0.3 Impact of climb assist

As Peterson et al. (2016) outlined, all facets of a role are required to be considered rigorously when developing a fitness standard whilst working in conjunction with the industry. This is to minimise the disparity between practice and research following separate paths to create an impractical fitness standard which cannot be tested empirically out with a lab setting, and may not be capable of being adhered to by a substantial minority of individuals. The questionnaire in chapter three and anecdotal evidence showed that climb assist systems are not in place across all turbines with only 37.5% of respondents stating the turbines they service have climb assist. However, this was not mentioned within the Renewable UK medical fitness guidelines (2013) and it is not known whether such systems were considered and the effect on the standard. Since the completion of chapter four, anecdotal evidence suggested that the potential lack of investment in climb assist system was in part due to a lack of supporting evidence. However, Barron et al. (2016) found that using a climb assist system when climbing at 24 rungs per minute (6.86 m per minute) led to a significant decrease in $\dot{V}O_2$ of 22.5%. The mean $\dot{V}O_2$ for the climb with and without climb assist were 22.0 (± 4.3) $ml.kg.min^{-1}$ and 28.3 (± 3.5) $ml.kg.min^{-1}$ with both values being below the Renewable UK (2013) fitness standard of 35.0 $ml.kg.min^{-1}$. The difference in values between this study and the work in chapters five and seven could be the speed of climbing (6.86 m per minute v. > 7.58 m per minute) and the sample population being habituated ladder climbers. The latter point means that the participants adapted their technique to minimise the impact of fatigue whilst climbing by leaning against the inside wall of the wind turbine tower for support. This again highlights the difference that working with industry could have as the nuances of the role such as adopting technique can be established and the effect of them recorded. Furthermore, this provides an example of the interaction between speed and energy demands as it can lower the demand placed on ladder climbers which could have longer term implications. The use of a climb assist could be an effective tool for reducing the physical strain placed on individuals which if installed on, for example, every turbine in the UK could lower the demand on ladder climbers. The implications of this could be three-fold with a reduction in the required fitness standard by virtue of the demand being lower through climb assist but due to the reduction in demand and effort, the daily climb limit could conceivably be raised. Finally, with further investigation, the "whole body effect" in terms of muscular activation, perceived exertion, force production, biomechanics and the cardiorespiratory impact could be better understood. Hypothetically if there is a reduction in strain or force production this may reduce the level of forearm strain which was reported by participants to be a limiting factor when completing the vertical ladder ergometer climbing. Oksa et al. (2014) found that vertical mast climbing led to an excessively high level of wrist flexors and extensors activation exceeding the recommended 14% MEMG with values of 24 ± 1.5 %MEMG) and extensor (21 ± 1.0 %MEMG). Stewart and Mitchell (2018) observed a significant decrease in mean left and right-hand grip strength after an 80 m vertical ladder ergometer at a self-selected speed immediately after and 15 minutes post climb. There was no difference in pegboard and hand tool dexterity scores immediately post climbing, the fact that these improved substantially after 15 minutes suggests that skill learning of these tests was incomplete. This potentially occurred due to participants still learning their optimal strategy for the task completion. Oksa et al. (2014) found high levels of muscular activation in the forearms in mast climbing and Stewart and Mitchell (2018) found that average grip strength did not recover within 15 minutes. This combined with the work in chapter three which highlighted that 90% of respondents undertook manual labour would suggest that the reduction in strain by the use of a climb assist system could only be positive when undertaking manual labour tasks. With a more long-term outlook load carriage in laboratory settings has seen neuromuscular recovery taking greater than 48 hours (Blacker et al. 2010). With reported climbing frequencies of between four and five days for 53% of chapter three's participants this would leave individuals with incomplete recovery. Should this occur in practice, individuals would be starting each working day without their ability to work at their optimal capacity which could impact on their work. Without empirical evidence, this is hypothetical, and remains an important area for future research. The potential impact of climb assist systems could be wide ranging and their long-term use will be of great interest when the renewables industry considers the design of a physical employment standard.

8.0.4 Impact of external loading

A second factor which was not explicitly mentioned in the Renewable UK (2013) Medical Fitness guideline was the expectation to or to not climb with an external load. Chapter seven highlighted that the use of 5 kg and 10 kg significantly ($p < 0.05$) increased oxygen consumption from a no-load condition (36.36 ± 3.74 $ml.kg.min^{-1}$) and the same observation was seen between loads of 5 kg and 10 kg. The implication of this could have a large effect on a physical employment standard as the mean $\dot{V}O_2$ values observed were 38.03 (± 3.53) $ml.kg.min^{-1}$ and 40.12 (± 3.88) $ml.kg.min^{-1}$ at a speed of 7.58 m per minute. Whilst these values are lower than observed at higher speeds there is a large effect ($d = 0.92$) on oxygen consumption when carrying 10 kg which was 5 kg lighter than the maximal reported in chapter 3. It would therefore be safe to assume that an increased external load would incur an increased oxygen consumption. Further to this the effect of PPE (Helmet, harness, clips, climbing boots, overalls) must be recognised as this could then increase the relative load inclusive of 10 kg load in a climbing bag from 17.0% to 23.5% for males and 19.4% to 26.7% for females. The combined effect of PPE and load carriage not only increases oxygen demand, but also affects neuromuscular fatigue which could, in turn affect subsequent task performance. There are also implications for temperature regulation, discomfort, and the need for fluids to be carried to mitigate dehydration risk. Finally, it must also be ascertained whether over a period of 15 minutes it is acceptable for participants to be working "very hard" to climb a ladder before undertaking another task and/or having to perform multiple climbs per day. Currently this is not reflected within the current standard but prior to any regulatory revision, further research must be undertaken. For instance, as highlighted in chapter seven the effect of load carriage is significant with physiological response as well as on climbing gait.

The work shown throughout this thesis highlights the unique nature of the role that wind turbine technicians undertake compared to employees in other industries. The nature of vertical ladder climbing for up to 80 m sets it apart from other industries and this alone initially makes it unique as the demands posed by vertical ladders significantly differ from that of pitched ladders (Barron et al. 2018). The work conducted within chapters five, six and seven provide a strong platform for highlighting this uniqueness but also underlining that engagement must take place with the industry to better understand climbing speeds. This is not only in terms of climbing capability, the acceptability of the required effort both physiologically and perceptually, but also the effect of fatigue on recovery and job performance. Further to this chapters six and seven outline that climb assist systems can reduce the strain on climbers whilst climbing with external loads attached asymmetrically to a harness significantly increase the demands. Chapter five showed that as the speed of climbing increased so did the oxygen consumption with the mean values for the all three speeds exceeding the minimum demand set by Renewable UK (2013). This was also seen during the unloaded condition in the previous chapter with a mean oxygen consumption (36.03 $ml.kg.min^{-1}$) exceeding 35 $ml.kg.min^{-1}$ at a speed of 7.58 m per minute. This suggests that even without taking account of loading or personal protective equipment (PPE), the demands may be higher than the industry minimum requirement. These studies depart from previous work on the physiology of ladder climbing or ladder climbing biomechanics by having been conducted on long vertical ladders or an ergometer and have a focus on the physiology instead of a slipping or risk perspective (Vi 2008; Armstrong et al. 2009; Pliner, Campbell-Kyureghyan & Beschorner 2014; Schoenberg, Campbell-Kyureghyan & Beschorner 2015; Barron et al. 2017; Barron et al. 2018). As a result this work provides new knowledge that could be pivotal to the industry. The generation of new research is required to inform the development standards and qualifications, such as the work conducted by Milligan (2013). These standards and qualifications need to be credible by the industry regulators, and findings published in peer-reviewed journals are the evidence of their robustness (Peterson et al. 2016). Taken together, this thesis research is novel and utilises a unique facility designed to replicate vertical ladder climbing in the safety of the laboratory. The use of a ladder ergometer allowed for the attainment of steady state oxygen consumption and the manipulation of climbing speeds to minimise confounding factors. The use of an ergometer provided the opportunity to assess climbing biomechanics over longer durations than possible with short ladders, without the technical challenges of long ladders. From this new knowledge has been generated on the effect of ladder pitch, the effect of climbing speed and the effect of external load. Observations regarding climbing gait and the potential nuances of climbing a ladder ergometer have highlighted that more research is required in this area. However, it is anticipated that this would require work with an industry partner to accomplish this. Nevertheless, this is difficult due to the financial pressures regarding switching off power generation which could be up to £25,000 per day for a 7 MW wind turbine. The wind energy industry is a young industry and is growing year on year, however, as the UK and the rest of the world continue to invest in renewable energy this will only increase the number of turbines around the world (GWEC 2017). These turbines will be subject to maintenance schedules or failures which could require individuals to ascend them without mechanical assistance. This research highlights a range of relevant effects which demonstrate that more can be done to support this unique industry in developing a bespoke fitness standard to reflect the distinctive demands placed on its employees.

8.1 Limitations

The largest limitation across chapters four, five and six is the sample population. The participants for the studies were healthy young active students rather than those currently or previously who worked in the industry. The mean age of those who participated in these studies were 19.8 to 21.1 y with mean body mass of 66.0 kg to 75 kg, respectively. Currently there is no published research on the body size of the wind energy industry but as mentioned in section 8.2, in the offshore wind market in Germany there are a high proportion (45.5%) of workers aged 35- 59 y. This makes the sample population in chapter three considerably younger although, Garrido et al. (2018) also reported that 43.3% of their respondents were 20 – 34 y but no spread of data was shown. There is a large difference in the age and mass of those who participated in the studies within this thesis than those who potentially work in the wind energy industry. The participants in this study were lighter than the wind turbine technicians weighed in chapter six (mean 81.3 kg) however, this sample was not necessarily representative of the industry as a whole. Further to this, when comparing the body mass index (BMI) of the participants in the lab-based studies to equivalent values to the in Scottish Health Survey (2017) the BMI values are substantially lower (22 $kg.m^2$ v 27 $kg.m^2$). Therefore, it would seem highlight likely that the lab based participants would typically be lighter than the industry technicians. However, in order to confirm this a more costly and extensive quota sampling study would be required. Whilst this may limit generalisability compared to the current industry, it is conceivable that the industry would look to recruit from university graduates. Therefore, these individuals could be similar to those who were sampled within the current studies however, this is speculation. It could be expected that individuals self-selecting into this sector may be fitter than their counterparts in other industries or are not adversely affected by the requirement for hard physical work, or both.

The use of a ladder ergometer for the laboratory testing allows for the analysis of variables for scientific interest but does not replicate climbing a ladder in-situ. When participants climb a ladder inside a wind turbine, anecdotal evidence suggests that different climbers take different strategies. For example, some participants aim to climb as fast as they can in order to reach the nacelle in the shortest period possible. However, this may not be feasible in all circumstances due to excessive height of some turbines. Another strategy employed is for individuals to climb and rest at different points during the climb up the ladder. This has been reported (Personal communication) to be at points where individuals feel tired or on platforms between section of the ladder when changing over safety lines. By contrast, it is not possible to realistically rest on the ladder ergometer due to its continual movement and the focus on variables such as heart rate (HR) and $\dot{V}O_2$. Altering the aim of the studies could reduce this limitation for example if the aim was to find the effect of external load on climbing 80 m whereby the main objective on interest could be time and rest could be factored in. The main variables of interest in these studies were HR and $\dot{V}O_2$ and as such require three to five minutes in order to reach steady state (Burnley and Jones 2007) and therefore a rest period would most likely prevent this from occurring. The probability of conducting research to control these variables properly inside a power generating turbine is vanishingly small. Firstly, the cost in lost revenue would be prohibitive. Secondly, the health and safety challenges are immense, and mandate qualifications, and assumed liabilities etc. As a result, the ladder ergometer represents a highly practical solution, albeit an imperfect one, to address many of the issues.

The work conducted in chapters six and seven highlighted that PPE can add substantially to the relative mass than individuals must bare when climbing. The inclusion of PPE would have increased the generalisability of the research to the wind energy industry as the conditions would have been more representative of real-world conditions. However, the practical limitations of using such equipment were impossible to overcome. An example of this would be the inclusion of replicating the vest and overalls by using a boiler suit for every participant (Renewable UK 2015). It is hypothesised that the ambient temperature of the laboratory is higher than that of a wind turbine, although this would depend on the time of year and the height in the turbine. It was reported in chapter three that the top of the tower becomes very warm and the technicians can open the nacelle roof hatch. This is most likely due to temperature stratification, leading to technicians first venting the nacelle as soon as they reach it, before commencing other duties. Whilst a warm lab may have replicated the conditions in the industry, the practical logistics of purchasing a large size range of overalls, and laundering these daily would have proved unassailable. By contrast, the use of full body harnesses and industry standard climbing bags ensured ecological validity of the load carriage experimental work.

It must be recognised that the use of a ladder ergometer may potentially lead to altered biomechanics relative to those in a wind turbine. This is due to the task required by the ladder ergometer demanding maintenance of a fixed speed, as opposed to a fixed ladder allowing for the possibility of speed variation. In biomechanical terms, the aim of ladder ergometer climbing is to maintain a fixed position as opposed to displacing the centre of mass vertically up a fixed ladder as height is gained. This may have led to participants subtly altering their climbing technique compared to when undertaking ladder climbing in-situ. However, this difference is likely to be small, because on the ladder ergometer, the centre of mass was moving by approximately 20 cm vertically and perhaps 10 cm horizontally, even if the torso (where the centre of mass (COM) is located) was fairly immobile during the climbing gait. However, without conducting a direct comparison in-situ it is difficult to estimate the effect of the ladder ergometer compared to vertical ladders. This piece of equipment is arguably the best available to study vertical climbing physiology and biomechanics, due to the limitations of conducting research on fixed ladders.

Finally, across most studies the lack of industry buy in and recruitment of those in the industry meant that there were small sample sizes of those in the industry, as in chapter three and six, or a lack of experienced ladder climbers participating in the laboratory-based studies. The limited contacts within the supervisory team were fully exploited, but despite this, reaching senior figures with decision-making and line management responsibilities proved problematic. There are several difficulties in accessing participants due to the double sub-contracting nature of the industry and often companies contracting out the servicing of turbines to other companies. The studies conducted were adequately powered but as previously discussed the recruitment of industry-based participants would improve the generalisability of the studies. Throughout this journey the number and level of contacts for the lead researcher and supervisory team have increased and had the research been conducted more recently the potential for buy in from the industry would most likely be greater.

8.2 Implications

The conducting of research in the field of human factors in renewable energy is increasingly more relevant as the UK 2020 target of 15% renewable energy becomes closer (UK Parliament 2016). This inevitably will lead to increased investment in wind energy both onshore and offshore with expected investment in offshore wind energy to reach £2.5 trillion (Renewable UK 2018). Whilst the UK outlook for offshore wind energy is due to increase from approx. 7.0 GW up to 30 GW by 2030 (Renewable UK 2018), the global wind energy rose to 2000 GW by 2010 (Renewable UK 2018). This all points towards an increased number of turbines being installed both on and offshore which ultimately will need serviced over time to keep them running optimally. Anecdotal evidence has suggested that the servicing takes place at regular anticipated and planned intervals but that if an issue occurs it is required to be fixed as any change in the turbine performance can lead to a dramatic reduction in revenue. Further to this, for offshore wind the servicing in general takes place during the summer where the weather conditions and sea-state are more stable and favourable for boat transport and servicing. It is generally accepted that most modern large wind turbines contain lifts, differing from the findings in chapter three, and whilst these minimise the need to climb turbines this does not eliminate this requirement entirely. In 2015 there was a fatal accident in Germany when a lift failed in a wind turbine which led to the suspension of the use of lifts pending an investigation into the accident (Vorhölter 2015). However rare such adverse events may be, they demonstrate the continuous requirement for the workforce to be capable of ladder climbing. In this example, a complete shut down of all turbine lifts by the manufacturer of the one affected, involved several months of mandatory unassisted ladder climbing by all technicians. The results of this body of work suggest that currently the Renewable UK (2013) fitness standard of 35 $ml.kg.min^{-1}$ underestimates the demands of vertical ladder climbing and is not representative of the demands placed on wind turbine technicians based on the work conducted. Further to this, chapter three found that 90% of individuals are undertaking manual work which will require physical strength to complete. When taking this into consideration in the context of the work by Oksa et al (2014) and Stewart and Mitchell (2018) the levels of forearm muscle activation are high in ladder climbing and lead to a reduction in grip strength post climb and 15 minutes post climb. The impact of this could lead to residual neuromuscular fatigue occurring for up to 72 hours (Oksa et al. 2014) and could be exacerbated by climbing multiple turbines in a day or climbing consecutive days. It is possible that the effect of such fatigue could increase the time taken and decrease the quality of work tasks in the nacelle leading to individuals becoming less efficient. This could be more pronounced during more physically arduous tasks such as gear box replacements compared to electrical or computer tasks. Based on the work conducted in this thesis, together with the fact that the work tasks undertaken are themselves strenuous, it would imply that the current fitness standard needs to be redeveloped to be more representative of the demands of the industry. Not only would this be to ensure that those in the industry are fit enough to climb a turbine tower, but also to ensure that they are then still able to complete their required tasks in an acceptable time.

When considering that not all individuals may be required to climb turbines for day to day work but in emergency situations for rescues or in the event of lift failure it could be worth considering a two-tiered approach to a fitness standard. This is based on the premise that the fitness demands to climb safely and then be in a physically recovered state in order to optimally complete tasks may lead to a higher physical employment standards (PES). The impact of this would be to ensure that individuals are working at a lower percentage of their maximum to establish that they are still able to complete their tasks in a relatively fresh condition. However, this could exclude a number of physically fit individuals from climbing turbines who are neither required to complete manual labour tasks nor to regularly climb turbines. For example, if an individual is only required to climb a turbine in a emergency, they could potentially be allowed to climb nearer their $\dot{V}O_2$ max than someone who climbs more regularly or multiple times per day. Hypothetically, this could be that in an emergency someone can climb at 80% of their maximum but if they climb daily it could be 60% of their maximum. These values are hypothetical but outline the difference of having a two-tiered system similar to that of the emergency medical technician in the oil and gas industry. The implication of understanding the demand of ladder climbing and how physically demanding it is could be the creation of a two-tiered system to better fit the industry and be more suitable to more individuals.

The investigations conducted have highlighted the lack of previous research within this unique and young industry. The implication of this is that for progression on the formation of a medical fitness standard more research needs to be conducted: validation for a ladder climbing fitness test; optimising the dose response of manual ladder climbing even though climb assist is available; gender differences and climbing performance; climbing performance and age; and rest interval post ladder climbing to the nacelle. Without this research the industry faces multiple risks some of which have already been outlined. Firstly, the recruitment of individuals who are not fit enough to climb the turbine or require considerable time to rest after reaching the nacelle. This is not only putting those individuals at greater risk than others but will have an impact on time effectiveness and task completion during a normal working day. In addition, future research should clarify the extent to which climb assist should be used, this is to ensure that the vital fitness of employees is not lost for when they are required to climb without them. There is potential that considerable recruitment is likely to be required in this expanding industry, however, very little is known regarding the potential long-term ill-effects of turbine tower climbing such as musculo-skeletal issues relating to overuse, or postural consequences. Whilst anecdotal evidence was gathered there is not known long term health implications. The industry will need to be inclusive with respect to men and women and an ageing workforce as Garrido et al. (2018) highlighted that 45.3% of the off shore wind farm demographic in Germany was 35-59 y. Furthermore, it should be recognised that the demographics of the working population as a whole, and this industry in particular are likely to undergo considerable change in the foreseeable future. As yet the extent to which ladder climbing capability is lost with age is unknown, and perhaps more crucially, the possible negative effects on the musculoskeletal system with age. There is potential that the largest implication of this research is that in knowing more about a unique industry it highlights how little is known and how much more work is required to be conducted by researchers and the industry.

8.3 Future Research

The implications of the new information provided by this thesis on vertical ladder climbing may impact the renewable wind energy industry and other related sectors. It highlights an urgent requirement for systematic programmes of research to aid in generating robust research to understand the demands of working within the wind energy sector. This underscores the importance of collaboration with the industry and a balance between the needs of the industry married with the robust processes of academic research, such as conducted by Milligan (2013). It must be recognised that when aiming to conduct research in conjunction with an industry that conflicts of interests may occur with individual companies with specific projects or certain products. Nevertheless, there is a growing collaboration within the industry with Innovate UK and Offshore Renewable Energy Catapult aiming to build an entrepreneurial industry with the support of government subsidies. It should also be recognised that wind turbines are depreciating assets and that any downtime for maintaining them equates to a loss in revenue. Therefore, as has been done in the North Sea offshore turbines, due consideration of preventive maintenance and in-situ repairs will assist in minimising this downtime. However, such considerations could then impact on the workforce if measures were taken to condense the servicing visits into a small-time window that required multiple turbines to be serviced a day or back to back days. There is potential that with typical wind farm life spans of 25 years that those turbines installed now will only require increasing levels of maintenance. The impact of this over a whole country or continent would lead to considerably more servicing hours. As yet the industry is ill-equipped to anticipate the impact of increased and more regularly servicing on the health and fitness of the workforce and as such, more research is required to be completed.

8.3.1 Industry related

As was outlined previously, the survey conducted in chapter three highlighted the small sample size and non-response bias, with the consequence that in order to gauge the overall landscape, an industry-wide survey should be undertaken. The multiple foci of such a study would include the day to day role of wind turbine technicians and its acceptability, the health of a wind turbine technician, the types of turbines climbed and the pre-climbing fitness requirements for working within the industry. As mentioned previously such questions could lead to conflicts of interest or companies not providing gatekeeper approval due to the responses having potential benefit to competitors. Therefore, this necessitates the need to work with industry bodies. Furthermore, this type of research would need to maximise its reach to companies of different sizes and sub-contractors. This is to ensure a true reflection of the industry as a whole and the work that takes place within it.

8.3.2 Health and fitness related

Borne out of the research conducted in chapters five to seven were a number of future research avenues that arose, some of these have already been proposed by Barron et al. (2016, 2018) in relation to vertical ladder climbing and the use of climb assist systems. A large avenue for future research would be vertical ladder climbing and the interaction with vocational tasks. With reference to vertical ladder climbing an acceptable climbing rate or rates are required to be agreed between academics and the industry as undertaken by Milligan (2013) with the Royal National Lifeboat Institute fitness standard. This is an important initial step towards a greater understanding of the interaction between physical demands and the work requirement of vertical ladder climbing. Subsequent steps will involve profiling the recovery from climbing at different speeds as this could impact the chosen climbing rate. These two factors are crucial when considering the acceptable climbing rate as it must be known how fit someone needs to be but how different speeds can influence recovery and impact on work done. As such, based on the work by Stewart and Mitchell (2018) and Oksa et al. (2014) understanding the impact of ladder climbing on muscular activation or the interaction of strength and ladder climbing could be crucial to understanding the requirement for recovery post climbing. To understand the effect of ladder climbing on tasks it is therefore necessary to understand what tasks are completed, which could be done by an industry wide survey as previously mentioned, and then understand the demands of such tasks in terms of level of general efforts, specific muscular effort, or requirement to work in confined spaces. Only with this global perspective could research be designed which is capable of generating an understanding of the impact of exertion and the recovery profile on vocational or industry-relevant tasks. As such this is a potentially complex area of investigation with multiple layers, formulating a research programme to inform the design of a fitness standard is challenging, and is likely to involve considerable resource.

It was outlined that climb assist systems significantly reduce the demands placed on individuals when climbing vertical ladders (Barron et al. 2017) and may have long-term implications for employee fitness. Whilst it was found that at 24 rungs per minute a climb assist device reduced the demands of ladder climbing, the interaction of climb assist and speed is not known. Future research should aim to profile the effect of climb assist at different speeds or acceptable speeds to understand the speed and climb assist interaction. It should be recognised though, that there is most likely a learning effect associated with such devices and that those using these devices previously may already have a preferred speed. Both of these factors could limit the possibility of achieving maximum benefit from a climb assist system. From a long term health perspective if an individual was to pass a fitness test on an unassisted wind turbine where by climbing multiple turbines or multiple days per week it is hypothesised that they receive a training stimulus by doing so. If a change was made to install climb assists on all turbines that they work on, it would be useful to understand the impact of assisted climbing on the employee fitness. It could be assumed that the training stimulus would significantly decrease which in the long term could have a detraining effect on the workers. If they then moved roles or there was a climb assist issue, long term habitual reliance on a climb assist device could potentially lead individuals having insufficient fitness to climb unassisted. This question of what is a sufficient climbing stimulus to create and maintain an enduring capability for fully manual climbing while maximising work capability (i.e. using climb assists to an extent) remains fundamental for the industry going forwards.

It must be recognised that the addition of external climbing loads needs to be fully investigated. Chapter three highlighted that wind turbine technicians climb with external loads up to 15 kg. There are many avenues to be considered around loaded climbing with perhaps the most prominent around acceptable climbing loads. This is not only a human factors issue but politically this may also be of interest to workers unions around what loads are acceptable or unacceptable to carry vertically in addition to the necessary PPE. The topic of the acceptable loads is a potentially contentious as it could lead to different weight allowances for different sized individuals or between genders. Drain et al. (2016) highlighted that increasing the load carried, increases the physiological demand which may in turn reduce the acceptable work duration. If strategies can be found to reduce the effect of loading, then these should be investigated. There is an awareness that the use of different load carriage systems and the positioning of loads can alter the demands of tasks. This is hypothesised to occur due to spreading the load carried over a larger number of muscles. This was seen by Birrell and Haslam (2010) who found “backloading” compared to a “standard load carriage system” and “airmesh” load carriage led to a significant reduction in forces at toe off. Furthermore, when a load was distributed evenly across the torso it reduced the maximum braking force by 10%. Lloyd and Cooke (2000) found increased economy when using an “AARN” pack that loaded both the front and back of the torso. This was suggested to the due to moving the load carried closer to the centre of mass (COM), compared to rucksack loading. Whilst interventions such as backpack loading or even vest loading, would most likely be impractical due to the harness it outlines that many avenues should be explored in order to ascertain a more complete picture of the effect of external load carriage on vertical ladder climbing. Therefore, it would be of interest to understand the implication not only on physiology of symmetrical loading but also biomechanics. Longer term research such as this could also lead to an enhanced understanding of musculoskeletal injuries if they occur in this field as it would be logical to assume that chronic asymmetrical loading could have an impact on the musculoskeletal system. Previous research has found that one in five firefighters have experienced a trip, slip or fall when carrying a hose over one shoulder (Petrucci et al. 2012). Furthermore, when walking asymmetrical loading has been shown to reduce co-ordination between limbs, as well as lead to increase front lean and higher ground reaction forces (Haddad et al. 2006; Zhang, Ye and Wang 2010) Therefore, the potential benefits to the industry of understanding the effect of loading and the position of loading potential help aid economy of effort as well as then link into the acceptable climbing speed, duration and their impact on the quality of work . This is necessary as it would be inappropriate to aim to ascertain appropriate climbing speeds without ensuring it replicates real world conditions as chapter seven showed that externally loading either 5 kg or 10 kg significantly increase oxygen consumption. Peterson et al. (2016) recommended that all aspects of load carriage be investigated, and due care taken to ensure that this is replicated within the research on physical employment standards. In the wind energy industry, when investigating the impact of load carriage there should be an understanding of the interaction between load carriage and climb assist. Climb assist significantly decreases the demand of ladder climbing unloaded, but it is unknown if its benefits are similar when carrying a load vertically. Therefore, the interaction between load carriage and climb assist could be of great interest to optimising work programmes and of interest to unions and companies when aiming to ascertain acceptable climbing loads. The depth of research required to be completed in the field of external loading is considerable, mandating a programme of both laboratory-based and turbine-based experimental studies. Furthermore, there needs to be an understanding of the relative reserve that an individual could be expected to have when climbing, and the inter-individual variability. This is not currently known but will be essential to inform future legislation and guidance.

8.3.3 Industry academia link

As has been outlined previously there are significant costs associated with conducting research within a wind turbine due to the necessity to shut the turbine down for research purposes. As a result, is it questionable whether extensive research could be feasible in a live wind turbine. There are many barriers to such research such as the cost-benefit relationship in doing so however, potentially working with industry bodies or research groups could open the doors to conducting robust necessary research. For example, it could become economically more feasible to have purpose-designed simulated turbine simulators such as short towers only for training purposes. However, a significant exception is in the ultimate validation of the ladder ergometer. Most of the research conducted during this thesis was completed on a ladder ergometer except for chapter six. Both from an occupational fitness test validity perspective, as well as physiological and biomechanics perspectives it would be of interest to understand the relationship between vertical ladder ergometer and vertical ladder climbing in-situ over a long distance and duration (> 30 m vertical height gained) Ultimately, there remain many unknowns which can potentially be investigated cost-effectively in laboratory settings if vertical ladder ergometers can undergo full validation. Secondly increased engagement with the industry would allow for the potentially greater recruitment of ladder climbing participants which would be of interest to both academia and the industry. As has been outlined through the thesis the perceptual and physiological response to various stimuli has not been consistent. It would be of interest to both to understand the reliability of RPE in both habituated ladder climbers and non-habituated climbers as this could potentially be a method of helping regulate climbing speed in-situ. This could be done in a laboratory situation ascertaining climbing speeds and physiologically responses to given RPE values as well as looking at how load interacts RPE also. Pragmatically, the industry will have to make decisions based on genuine human capabilities and develop its recruitment and occupational testing strategies accordingly.

9.0 Conclusion

The renewable sector, across all forms, is growing year on year, and, with increased worldwide political shifts recognising the reality and gravitas of global climate change, such as the Paris agreement, this is set to increase. The forecast increase in wind energy up to 2040 suggests that there are going to more turbines put in place which ultimately will need serviced and repaired. To cope with this increase demand for wind energy, the workforce building and maintaining turbines will expand rapidly and substantially. To date this industry is very young with the first industry body in the UK being formed 40 years ago and, unlike other sectors, research conducted within this field is lacking. As such this led to Renewable UK (2013) adopting a fitness standard from another industry (Personal communication) which, although comparable, fails to replicate precisely the demands of the wind energy industry. Not only is the exertion required of technicians much greater than 'seemingly comparable' industries by virtue of the vertical orientation, distance climbed, and loading, but the current occupational fitness test for wind technicians could enable employees to pass, who are significantly less fit than necessary to enable them to climb without mechanical assistance.

This work has highlighted the not only the complex nature of physical demands wind turbine technicians face but also that the current fitness standard is not reflective of the demands of vertical ladder climbing. This thesis in part completed the first aim of understanding the day to day role of a wind turbine technician. Chapter 4 highlighted that participants climbed turbines 3 to 5 days per week with external loading (up to 15 kg) but that climb assists systems or lift were not present in the majority of their turbines. Furthermore, 62.5% sometimes or often (37.5%) worked in a restricted space and the tasks they completed differed in demand compared to the ground due to restricted space. This provided a perspective going forwards of areas for future research. Based on this survey chapters five to seven highlighted that the current fitness standard is not appropriate for the current industry. This is because vertical ladder climbing is significantly more demanding than that of pitched and therefore, recycling a fitness standard was not appropriate. Secondly, the value of 35 $ml.kg.min^{-1}$ was exceeded climbing both unloaded and loaded depending on the speed and load which suggests that the value should be revisited. Furthermore, if the use of climb assist devices are to be considered then this could potentially lower the required fitness requirement due to it significantly reducing the demand of vertical ladder climbing. However, consideration must be give to when absent or unserviceable, technicians are required to climb a vertical ladder, which can put a significant and potentially excessive demand on workers, unless they are habituated to the task. Furthermore, a greater understanding of the relationship between RPE and ladder climbing is required as this could be tool used to help regulate climbing speed in the field but a greater understanding of it is required to do so. This work aligns with step one of Petersen et al. (2016)

guidelines for creating a physical employment standard by highlighting that one is required. The work conducted in this thesis highlights that currently the medical fitness standard within the UK neither adequately nor accurately represents the demands placed on wind technicians. As the sector undergoes expansion and the industry matures, it is clear that research is urgently required to inform the process of reshaping the medical fitness standard to one that is both vocationally relevant and safe. Future research should consider the long term implication and the interaction of external factors such as external load and climb assist in relation to physical employment standards and daily work limits.

10.0 Appendix I Job Advertisements

Operations Engineer

WPO ★★★★☆ 2 reviews - Bramhall

Our company

The WPO Group is an independent European platform of renewable energy expert-services. Our clients are asset owners, investors, lenders and insurers. By providing asset management services on 3GW of wind and solar sites with a capital value of €4bn generating €750m of electricity sales annually, WPO is the market leader in France, UK, Ireland and Sweden. Our integrated service offering also includes technical due-diligence, asset inspections, testing and insurance brokerage. WPO currently operates across 9 European countries through 24 offices or service points.

Scope of Responsibility includes: Operational management of wind farms:

- Working with all parties to ensure that contractual obligations are fulfilled on a day to day basis.
- Acting as the key point of contact for our clients & service suppliers
- Preparing technical answers to queries either directly to clients or via our technical support resource pool.
- Guidance of the other Operations Engineers and Field Technicians in the compilation of accurate preliminary and monthly operations reports for presentation to the customer (wind farm owner). This includes preliminary and monthly reports that analyse down time & provide availability analysis.
- Checking, validating and sending to clients wind farm monthly reports
- Becoming an expert in our bespoke monitoring and reporting systems (training will be provided).
- Liaison with technical services to ascertain the cause of turbine failures, response times and works undertaken.
- Developing systems and procedures to ensure asset optimisation.

Duties also include, but are not limited to:

- Proactive monitoring of operating sites in conjunction with other team members.
- Follow up any performance issues
- Obtain all current service/maintenance records
- Monitor and/or maintain site activity records
- Monthly & annual availability performance and any subsequent claims
- Advising WPO field based staff regarding reactions to alarms from turbine monitoring systems when a turbine is unexpectedly taken "off line".
- Reporting all concerns raised by proactive monitoring and the general operation/maintenance of the wind farm to both the owner and the maintainer as appropriate.
- Organising repairs/statutory inspections as appropriate.
- Maintaining a calendar of servicing plans, weekly movements, statutory inspections etc.

Personal Skills / Attributes

You must have excellent attention to detail as producing reports, data gathering and continuous monitoring of sites need to be accurate at all times. You'll be working within a small team within a fast paced environment, so having a good sense of humour and being able to work in an organised manner is key. A flexible attitude is essential as occasional "out of normal hours" work may be required (although there is a 24/7 Operations Control service and regional staff out in the field who will cover most eventualities on site).

Education and Qualifications

You must be qualified to at least Degree level in a relevant Engineering / Technical area. Occasional travel to sites will be a requirement of this role so you will need to hold a current, full drivers licence.

A proven track record and experience from within the renewable industry, especially Wind Power will be highly advantageous.

Join us if you are looking for a competitive pay structure, private health care, 25 day holidays and pleasant working conditions. But just as importantly, join us if you are keen to work in a highly motivated and flexible environment and would like to be part of a team who are passionate about renewable energy. Apply now if we sound like the kind of company you would be proud to be a part of.

Job Type: Full-time

Required education:

- Bachelor's

Required experience:

- renewables, ideally wind energy: 1 year
- generating reports: 1 year

Required licence or certification:

- Driving licence

14 days ago - save job

» Apply Now

Please review all application instructions before applying to WPO.

14 people have already applied to this job on Indeed.

Apply Now

Other jobs you may like

VIE Operations Engineer Manufacturing Develop...
Solvay - Oldbury
10 days ago

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RECRUITMENT GROUP
GLOBAL TALENT DELIVERY

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Job Details

Candidates

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Job Details:

Job category: Engineering
Company: CVWOW
Location: Aberdeen
Salary: Competitive
Job type: Permanent
Full/part time: Full time
Job reference: BV-ET-ABER
Date advertised: 24/01/2017

Electrical Technician

Electrical Technician
Location – **Aberdeen / Boyndie**

KUDOS RECRUITMENT GROUP GLOBAL TALENT DELIVERY

This vacancy was placed on 24/01/2017 by Kudos Recruitment.

ENERCON is one of the markets leader's in the wind energy industry. Represented in 36 countries, we provide the production, construction and maintenance of wind turbines.

As an Electrical Technician, you will be travelling around our sites in and around Aberdeen (and occasionally around the UK), installing components, reporting, maintaining and fault finding on our ENERCON turbines.

Responsibilities –

- Carry out the maintenance & repairs of the turbines when instructed
- Installation and retrofitting of key electrical components
- Carry out risk assessments and method statements when and where necessary
- Write a detailed report on the repairs and what was carried out after work is completed
- Adhere to all relevant health and safety requirements
- Assist in mechanical maintenance as and when required
- When and where necessary, travel to WEC sites throughout the UK, Germany and possibly elsewhere in Europe.

You will be climbing the wind turbines on a daily basis; excellent with heights is a requirement. A proactive, motivated, resourceful, team player is needed in this challenging and exciting position. Ability to stick to deadlines and finish work to the highest standard is required.

Skills and requirements

- Level 3 electrical qualifications; ideally you will be a time served apprentice
- Ideally an Engineering degree or similar
- Ability to fault find and report on electrical issues.
- Highly health and Safety conscious.
- Ideally experienced in commercial and/or industrial electrics.
- Experience with maintenance schedules.
- A full (clean) driving license is essential
- Excellent health and fitness levels are essential for this role.
- Must be good with heights
- A team player, flexible and resourceful individual is required for our teams.

Please be aware the role will involve periods of time staying away from home

We offer a very competitive basic salary and OTE circa £30,000 - £32,000, a private pension scheme, private healthcare, friendly and helpful colleagues and fully paid accommodation whilst travelling, what more could you wish for in your new career? If you want to become a member of the future, now is the time to apply!

No terminology in the advert you have seen is intended to discriminate on the grounds of age, gender, race, colour, religion, disability or sexual orientation, and we will gladly accept applications from all sections of the community.

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Candidates

- JOB SEARCH
- CANDIDATE LOGIN
- REGISTER

Job Details:

Job category: Customer Services
Company: CVWOW
Location: Coleraine
Salary: Competitive
Job type: Permanent
Full/part time: Full time
Job reference: BV-FST-COL2
Date advertised: 30/01/2017

Field Service Technician

This vacancy was placed on 30/01/2017 by Kudos Recruitment.

We are recruiting for 2 Field Service Technicians

Location: **Coleraine, Northern Ireland**

ENERCON is one of the markets leader's in the wind energy industry. Represented in 36 countries, we provide the production, construction and maintenance of wind turbines.

As a Field Service Technician, you will be travelling around Northern Ireland sites installing components, reporting, maintaining and fault finding on our ENERCON turbines. You will be climbing the wind turbines on a daily basis

Field Service Technician Responsibilities -

- Service, maintenance and repair of ENERCON wind turbines in the surrounding areas from the base location
- Responsible for a variety of state of the art electrical, electronic and mechanical equipment
- Maintain excellent communication with all departments
- Responsible for completing all computerised documentation
- Weekend emergency call out service and late shift work involved

The initial training for this position will take place in one of our Service Stations in Donegal / Sligo for a minimum period of three months where accommodation will be provided to the successful candidate.

Field Service Technician Skills and Requirements -

- Qualified as an Electrical Technician (e.g Electronic / Electrical Engineering / Electrician) with experience working in eith the power generation, aerospace, industrial, agricultural or automotive industries Level 3 Qualification in a relevant associated subject
- Previous experience working on wind turbines is an advantage
- Full clean driving licence and Safe Pass Card / Construction Skills Register (CSR) are essential
- Flexibility and high mobility required - willingness to travel to meet the companies' requirements
- Have a positive, pro-active approach to working in a team environment along with excellent organisational and interpersonal skills
- Physically fit and comfortable with heights
- IT Skills essential

A proactive, motivated, resourceful, team player is needed in this challenging and exciting position. Ability to stick to deadlines and finish work to the highest standard is required.

Please be aware the role will involve periods of time staying away from home including a training period of between 3 – 6 months within a service team based ir

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- IT Skills essential

A proactive, motivated, resourceful, team player is needed in this challenging and exciting position. Ability to stick to deadlines and finish work to the highest standard is required.

Please be aware the role will involve periods of time staying away from home including a training period of between 3 – 6 months within a service team based in Ireland.

We offer a very competitive basic salary and OTE, a private pension scheme, private healthcare, friendly and helpful colleagues and fully paid accommodation whilst travelling, what more could you wish for in your new career? If you want to become a member of the future, now is the time to apply for the role of Field Service Technician!

No terminology in the advert you have seen is intended to discriminate on the grounds of age, gender, race, colour, religion, disability or sexual orientation, and we will gladly accept applications from all sections of the community.

APPLY NOW »

Job Summary:

SHARE ON:

Field Service Technician

Salary: Competitive
Job type: Permanent
Location: Coleraine
Job reference: BV-FST-COL2
Date advertised: 30/01/2017

APPLY NOW »

11.0 Appendix II Wind Turbine Technician Survey

ROBERT GORDON UNIVERSITY ABERDEEN

Wind Turbine Workers Questionnaire

Introduction

This questionnaire is designed for those who work on wind turbines and have to climb or take a lift to the top of the tower to complete tasks. If your role is solely in the constructions of wind turbines you are excluded for taking part in this questionnaire.

The purpose of this questionnaire is to gain an understanding of those working in the wind energy sector and the demands of jobs of those who climb wind turbines. This will inform future research projects investigating the wind energy sector and identify relevant research which can be effectively undertaken in a laboratory setting. These research areas will aim to tie in with the needs of the industry in order to improve working practice.

All data will be confidential and treated anonymously and no person identifable data is being collect from the survey. However, the results of this study may be used in a future publications. By taking part in the survey you are providing your consent to take part in the study and that the data collected may be used for publication. If you wish to provide contact details in order to provide further information or wish to be informed of future studies email myself at p.barron@rgu.ac.uk.

To complete this questionnaire answer each question as fully and honestly as possible. Once you have completed all the questions on a page follow the next arrow at the end of the page.

The questionnaire will take 10-20 minutes to complete. Thank you in advance for your participation. If you have any questions contact PJ Barron at p.barron@rgu.ac.uk

1

ROBERT GORDON UNIVERSITY ABERDEEN

Wind Turbine Workers Questionnaire

Wind Turbine Questions

1. How long have you worked in the wind turbine industry?

- Less than 1 year
- 1 to 3 years
- 3 to 5 years
- More than 5 years

If longer than 5 years please specify

2. What height of turbines do you typically work on?

Please answer in metres

3. On average how many days per week does your work involve climbing a wind turbine?

Please select the appropriate number of days

0 1 2 3 4 5 6 7

4. On average how many times a day would you climb a turbine (Either the same turbine or different ones)?

Please Estimate

5. On average how long in total do you spend climbing a wind turbine each day?

- Less than 15 minutes
- 16 to 30 minutes
- 31 to 60 minutes
- More than 60 minutes

If more than 60 minutes please approximate

2

ROBERT GORDON UNIVERSITY ABERDEEN

Wind Turbine Workers Questionnaire

Wind Turbine Questions

* 6. Please Estimate the typical total daily height you climb (In metres)

* 7. Please estimate the maximum height you have **EVER** climbed in a day (In metres)?

* 8. Do you use a climbing bag?

○ Yes ○ No

Please provide details on the make and model if possible

9. If yes to Q.8 approximately (In kilogrammes) how much weight do you carry in your climbing bag?

ROBERT GORDON UNIVERSITY ABERDEEN

Wind Turbine Workers Questionnaire

Task Related

* 10. What type of tasks do you perform when working in a wind turbine?

Select all which apply

- [ ] Computer Tasks
- [ ] Manual Labour
- [ ] Construction
- [ ] Electrical
- [ ] Other (please specify)

* 11. Do the tasks you complete have different demands when completing them in a wind turbine compared to on the ground?

- ( ) Yes
- ( ) No

12. If you answered yes to Q.11 please describe the specific differences?

Fatigue

Space Constraint

Noise

Temperature

Ambient Light

Other (Please Specify)

ROBERT GORDON UNIVERSITY ABERDEEN

Wind Turbine Workers Questionnaire

Task related

13. Are any of your tasks difficult to perform due to the nature of the wind turbine?

Please tick one

○ Yes ○ No

If yes please provide further details

* 14. On a wind turbine is it necessary for you to have a recovery period after climbing before completing a task?

○ Yes ○ No

If yes please state the rest period required

* 15. Are there particular aspects of your day to day work which you think could be investigated or improved upon?

○ Yes ○ No

If yes please provide further details

ROBERT GORDON UNIVERSITY ABERDEEN

Wind Turbine Workers Questionnaire

Turbine Design

* 16. Do you sometimes have to work in any form of restricted space?

A restricted space is defined as an external constraint on body movement necessary for work to be carried out

○ Never ○ Rarely ○ Sometimes ○ Often

Please Provide Details

* 17. Are there any constraints that affect your posture when climbing the wind turbine such as the cone of the tower on your back?

○ Never ○ Rarely ○ Sometimes ○ Often

Please Provide Details

18. Based on q.17 is this further affected by personal protective equipment (PPE)?

○ Yes ○ No

Please provide details

ROBERT GORDON UNIVERSITY ABERDEEN

Wind Turbine Workers Questionnaire

Turbine Design

* 19. Does the ladder width and/or rung spacing differ in design from turbine to turbine?

○ Yes ○ No

If yes, please describe the differences

* 20. Do the wind turbines you maintain have lifts?

○ Yes ○ No ○ Sometimes

If yes, how many vertical metres do you have to climb yourself in a turbine with a lift?

Please estimate in metres

* 21. Do the wind turbines you maintain have a climb assist system?

○ Yes ○ No ○ Sometimes

7

ROBERT GORDON UNIVERSITY ABERDEEN

Wind Turbine Workers Questionnaire

Training

22. What training is currently provided on ladder climbing?

* 23. Is any physical testing completed before being given clearance to work on turbines?

Yes No

If yes, please describe the test

24. Is any physical training provided before being given clearance to work on turbines?

Yes No

If yes, please describe the training

25. Is any advice on physical training provided before being given clearance to work on turbines?

Yes No

If yes, please describe the training

26. Do you perform any regular exercise?

◯ Yes ◯ No

If yes, what exercise do you do and do you use this to reduce fatigue for ladder climbing?

ROBERT GORDON UNIVERSITY ABERDEEN

Wind Turbine Workers Questionnaire

Cold Ambient Conditions

27. Do the cold ambient conditions inside the turbine affect your ladder climbing?

○ Never ○ Rarely ○ Sometimes ○ Often

Please describe

28. Do the cold ambient conditions inside the turbine affect your ability to complete maintenance tasks?

○ Never ○ Rarely ○ Sometimes ○ Often

Please describe

ROBERT GORDON UNIVERSITY ABERDEEN

Wind Turbine Workers Questionnaire

Hot Ambient Conditions

29. Do the hot ambient conditions inside the turbine affect your ladder climbing?

- [ ] Never
- [ ] Rarely
- [ ] Sometimes
- [ ] Often

Please describe

30. Do the hot ambient conditions inside the turbine affect your ability to complete maintenance tasks?

- [ ] Never
- [ ] Rarely
- [ ] Sometimes
- [ ] Often

Please describe

ROBERT GORDON UNIVERSITY ABERDEEN

Wind Turbine Workers Questionnaire

Demographic Information

The questions in this section are to gather basic demographic data such as gender and age.

31. Are you male or female?

◯ Male ◯ Female

32. What height are you?

Please complete one

In feet and inches

In centimetres

33. What is your age (today)?

34. What is your body weight?

Please complete one

In stones and pounds

In kilogrammes

12

ROBERT GORDON UNIVERSITY ABERDEEN

Wind Turbine Workers Questionnaire

Questionnaire completed

Thank you for taking part in this questionnaire
The information you have provided is very important to us and will be used to inform future research relevant to the wind energy sector.
If you wish to provide further information or be contacted about future research projects please contact PJ Barron at p.barron@rgu.ac.uk.

12.0 Appendix III Reliability study participant information sheet

SRRG reference number: SHS/15/03

26th January 2016

Study Title: A physiological and psychophysical assessment of angled ladder ergometer climbing

Introduction.
My name is PJ Barron and I am a PhD student at The Robert Gordon University. As part of my PhD I am undertaking a study to assess the reliability of climbing a 75 degree ladder ergometer. Whilst there are some reported values on the physiological cost of ladder ergometer climbing at 60 degrees there is none at 75 degrees. The reasoning for this study is to assess the reliability of ladder ergometer climbing at 75 degrees. This will allow us to know understand the physiological demands of ladder climbing at 75 degrees and compare to previous literature.

We are inviting male participants to take part in this research. We are recruiting healthy males between the ages of 18 – 35 years to take part in this study.

Taking part in the study.
For this study we will be asking participants to come to the Sir Iain Wood Building (SIWB) at RGU on 4 occasions; once for familiarisation and 3 times for testing on the ladder ergometer.

Each session shall last no longer than one hour. You shall complete a warm up on the ladder ergometer and then during the complete 5 minutes climbing at 3 different speeds with 5 minutes rest between each bout before cooling down (a total of 25 minutes exercise including warm up and cool down). During this time oxygen consumption and heart rate shall be measured. To do this a belt will be fitted round your chest and you will be required to wear a small mask over your nose and mouth, which monitors the air you breathe in and out. You will also be asked to indicate how hard you feel you are exercising at, at each climbing speed.

If you agree to participate, we will ask you to come to the research lab in SIWB at a mutually suitable time for a familiarisation session. This will comprise completion of the PAR-Q form (attached to this letter) to ensure you are fit enough to participate. We will then ask you if you have any further questions about the study and ask you to sign two consent forms, consenting to participate of which you shall keep one copy and I shall keep the other. Your height and weight measurements will be taken. You will need to wear sports gear such as shorts, t-shirt and trainers for this. Private changing facilities are available.

After the end of the familiarisation session we shall then arrange the two further sessions, if you wish to participate in the study.

You are eligible to take part in this study if you:

- Male, between the ages of 18 – 35 years.

You are not able to take part in this study if:

- You have had any injury within the past month or any persistent pain from previous injury
- You take medication which affects your heart
- You answer yes to any of the PAR-Q screening questions

At the end of the study we will send you a summary report of the research.

No payment will be offered for your participation.

You may withdraw from the research at any time without giving a reason.

Advantages to participating
There will be no direct advantage to you for participating in this research. The findings will add to our current knowledge of the physiological demands of climbing on a ladder ergometer.

Disadvantages to participating
There is a possibility of transient muscle soreness if you are not used to exercising in this way but you shall not be at any greater risk than performing any other form of exercise for 25mins. This possibility will be reduced by you ensuring that you do the warm up exercise described on the exercise sheet. No other disadvantage is foreseen.

Confidentiality and anonymity
All the data we collect from you will be anonymised i.e. your name will not be able to be linked to the measurements or diary entries. In addition, your participation in this study will be confidential and we will not disclose the names of our participants. Your data will only be seen by the researcher and their research supervisors. Analysed data will be presented in a research report and paper but no one will be able to identify individuals from that.

All data will be collected and stored within the requirements of the Data Protection Act (1998).

Any questions?
If you have any questions please contact PJ at the address below.

What happens if there is a problem?
Please discuss any problems with us, the researchers or our supervisor. Our contact details are given at the bottom of this letter. If you have a complaint please send details of this to the convenor, School of Health Sciences Research Review Group, Robert Gordon University, Garthdee Road, Aberdeen AB10 7QG l.a.alexander@rgu.ac.uk or Mrs Elizabeth

Hancock, Head of School of Health Sciences, Robert Gordon University, Garthdee Road, Aberdeen AB10 7QG l.hancock@rgu.ac.uk

What will happen to my research data?
A research report and paper will be written as part of my PhD and may be more widely disseminated in academic and professional journals and conferences. The data we collect from you will be destroyed at the end of the research study once all the reporting is complete.

What happens now?
Please feel free to discuss this letter with your family and friends. If, after consideration, you would like to take part in this study please contact PJ Barron at the address below.

Thank you for taking the time to read this letter.

Researcher: PJ Barron PhD Student Institute of Health and Welfare Riverside East Robert Gordon University Garthdee Road Aberdeen AB10 7GJ Email: p.barron@rgu.ac.uk	Research Supervisor: Dr Arthur Stewart Institute of Health and Welfare Riverside East Robert Gordon University Garthdee Road Aberdeen AB10 7GJ Email: a.d.stewart@rgu.ac.uk Tel: 01224 262551

13.0 Appendix IV Informed Consent form

ROBERT GORDON UNIVERSITY ABERDEEN

Informed Consent Form

SRRG Ref No:	SHS/15/03
Title (short):	Vertical and Slanted Ladder Ergometer Climbing
Researcher	Peter-James Barron

	Please initial each box
1. I confirm that I have read and understand the participant information sheet dated 01/02/15 for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily.	
2. I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason.	
3. I understand that data collected during the study will be looked at by individuals from Robert Gordon University where it is relevant to my taking part in this research. I give permission for these individuals to have access to the data.	
4. I agree to take part in the above study.	

Participant:	
Name:	
Signature:	
Date:	

Person taking consent:	
Name:	
Signature:	
Date:	

Two copies to be completed one for the research and one for the participant

14.0 Appendix V Pre activity readiness questionnaire

Physical activity readiness questionnaire (PAR-Q) (SHS/15/03)

1. Personal information

Surname : ……………………………. Forename(s) : ……………………………...

Date of birth : …………………………. Age : ………………………………………...

2. Additional information

a. Please state when you last had something to eat / drink……………………...

b. Tick the box that relates to your present level of activity:

Inactive ☐ moderately active ☐ highly active ☐

c. Give an example of a typical weeks exercise:

……………………………………………………………………………………………...

d. If you smoke, approximately how many cigarettes do you smoke a day……..

3.	Are you currently taking any medication that might affect your ability to participate in the test as outlined?	YES	NO
4.	Do you suffer, or have you ever suffered from, cardiovascular disorders? e.g. Chest pain, heart trouble, cholesterol etc.	YES	NO
5.	Do you suffer, or have you ever suffered from, high/low blood pressure?	YES	NO
6.	Has your doctor said that you have a condition and that you should only do physical activity recommended by a doctor?	YES	NO
7.	Have you had a cold or feverish illness in the last 2 weeks?	YES	NO
8.	Do you ever lose balance because of dizziness, or do you ever lose consciousness?	YES	NO
9.	Do you suffer, or have you ever suffered from, respiratory disorders? e.g. Asthma, bronchitis etc.	YES	NO
10.	Are you currently receiving advice from a medical advisor i.e. GP or Physiotherapist not to participate in physical activity because of back pain or any musculoskeletal (muscle, joint or bone) problems?	YES	NO

11.	Do you suffer, or have you ever suffered from diabetes?	YES	NO
12.	Do you suffer, or have you ever suffered from epilepsy/seizures?	YES	NO
13.	Do you know of any reason, not mentioned above, why you should not exercise? e.g. Head injury (within 12 months), pregnant or new mother, hangover, eye injury or anything else.	YES	NO

Nb. Participant must answer no to questions 3-13 to be deemed as healthy.

Signature of Participant : .... Date : ....

Name of Supervisor : ....

Signature of Supervisor : .... Date : ....

15.0 Appendix VI Calibration procedure for Cosmed K4 B^2

1. Charge batteries until the lights on the charging unit were green
2. Connect the K4 B^2 unit to the charging unit and plug in. Power on the main unit and allow to warm up for 15 minutes
3. Once the unit has warmed up connect the K4 B^2 unit to a fully charged battery
4. Once connected undertake a room air calibration on the main unit. Once completed it will say calibration done. If the unit does calibrate it will say calibration failed, in this case repeat.
5. Complete a reference gas calibration with gas concentrations of O_2 = 16% and N_2 = Balance.
6. Commence the reference gas calibration and follow the instructions on the K4 B^2 unit. If reference gas calibration fails, repeat the process.
7. Commence the turbine calibration process. Connect the adaptor for the calibration syringe to the turbine which was inserted in the optoelectronic reader and sampling line connected.
8. Follow the instructions on the K4 B^2 unit for inward and outward motion of the 3 L syringe.

16.0 Appendix VII Chapter six participant information sheet

ROBERT GORDON UNIVERSITY ABERDEEN

SRRG reference number: SHS/15/23

15th July 2015

Study Title: An investigation of the effect of "climb assist" on the demands of ladder climbing (SHS/15/23)

Introduction.
My name is PJ Barron and I am a PhD student at The Robert Gordon University. As part of my PhD I am undertaking a study to investigate the effects of the "climb assist" device. There is some research which has investigated the energy costs of ladder climbing but no one has investigated the effect of climb assist. The reasoning for this study is simple: it will determine whether climb assist reduces effort and the energy cost of ladder climbing. This research will also be the first of its kind to measure the physiological effect of using a climb assist system to climb a vertical ladder.

We are inviting certified and approved (by Capital Safety Labs) ladder climbers to take part in this research. We are recruiting 8 subjects either male or female to take part in this study.

Taking part in the study.
For this study we will be asking participants to come to the TAG training facility, near Oldham for approximately one hour to complete a testing session.

Each session will last no longer than one hour. The testing process will be fully explained to you and you will have the opportunity to ask questions. You will then be asked to complete a consent form and a pre activity readiness questionnaire (PAR-Q) before having your height and body weight measured. You will be asked to complete two 5-minute bouts of ladder climbing once with climb assist and once without, with a ten-minute rest period between each bout. The order of these will be determined randomly. During these bouts oxygen consumption and heart rate will be measured. To do this a belt will be fitted round your chest and you will be required to wear a small mask over your nose and mouth, which monitors the air you breathe in and out. You will also be asked to indicate how hard you feel you are exercising using an established rating scale. Your climbing speed will be fixed at 24.5 rungs per minute through the aid of a metronome which will make a noise every time to you are take a step.

If you agree to participate, we will ask you to come to the TAG training lab at a pre-arranged time. Prior to arriving please complete the PAR-Q form (attached to this letter) to ensure you are fit enough to participate. We will then ask you if you have any further questions about the study and ask you to sign a consent form; you will be given a copy of the form and this information sheet to keep. Your height and weight measurements will be taken. You will need to wear the appropriate personal protective equipment for this test which will be supplied by Capital Safety Labs. Private changing facilities are available.

You are eligible to take part in this study if you:

- Are a capital safety lab certified ladder climber

You are not eligible to take part in this study if:

- You have had an injury within the past month or you have persistent pain from a previous injury
- You take medication which affects your heart
- You answer yes to any of the PAR-Q screening questions

At the end of the study we will send you a summary report of the research.

No payment will be offered for your participation.

You may withdraw from the research at any time without giving a reason.

Advantages to participating
There will be no direct advantage to you for participating in this research. The findings will add to our current knowledge of the physiology of vertical ladder climbing as well as helping to establish the effect of climb assist, which will benefit the industry as a whole.

Disadvantages to participating
There is a possibility of transient muscle soreness if you are not used to exercising in this way, but you will not be at any greater risk than performing any other form of exercise for 10 minutes. No other disadvantage is foreseen.

Confidentiality and anonymity
All the data we collect from you will be anonymised i.e. your name will not be able to be linked to the measurements. In addition, your participation in this study will be confidential and we will not disclose the names of our participants to anyone. Your data will only be seen by the researcher and his academic supervisors. Analysed data will be presented in a research report and paper but illustrations depicting the study will be constructed such that no one will be able to identify individual participants.

All data will be collected and stored within the requirements of the Data Protection Act (1998).

Any questions?
If you have any questions, please contact PJ at the address below.

What happens if there is a problem?
Please discuss any problems with me, the researcher, or my supervisor. Our contact details are given at the bottom of this letter. If you have a complaint please send details of this to the convenor, School of Health Sciences Research Review Group, Robert Gordon University, Garthdee Road, Aberdeen AB10 7QG l.a.alexander@rgu.ac.uk or Mrs Elizabeth Hancock, Head of School of Health Sciences, Robert Gordon University, Garthdee Road, Aberdeen AB10 7QG l.hancock@rgu.ac.uk

What will happen to my research data?
A research report and paper will be written as part of my PhD and may be more widely disseminated in academic and professional journals and conferences. The data we collect will be retained for up to 10 years in accordance with data management principles and practice which apply at RGU.

What happens now?
Please feel free to discuss this letter with your family and friends. If, after consideration, you would like to take part in this study please contact Rob Hirst (rhirst@capitalsafety.com) to arrange a suitable time for taking part in the study or PJ Barron at the address below.

Thank you for taking the time to read this letter.

Researcher: PJ Barron PhD Student Institute of Health and Welfare Riverside East Robert Gordon University Garthdee Road Aberdeen AB10 7GJ Email: p.barron@rgu.ac.uk	Research Supervisor: Dr Arthur Stewart Institute of Health and Welfare Riverside East Robert Gordon University Garthdee Road Aberdeen AB10 7GJ Email: a.d.stewart@rgu.ac.uk Tel: 01224 262551

17.0 Appendix VIII Chapter six PARQ

Physical activity readiness questionnaire (PAR-Q)

1. Personal information

Surname : …………………………… Forename(s) : ……………………………

Date of birth : …………….............. Age : ………………………………………..

2. Additional information

a. Please state when you last had something to eat / drink………………………

b. Tick the box that relates to your present level of activity:

Inactive ☐ moderately active ☐ highly active ☐

c. Give an example of a typical weeks exercise:

……………………………………………………………………………………………

d. If you smoke, approximately how many cigarettes do you smoke a day…….

3.	Are you currently taking any medication that might affect your ability to participate in the test as outlined?	YES	NO
4.	Do you suffer, or have you ever suffered from, cardiovascular disorders? e.g. Chest pain, heart trouble, cholesterol etc.	YES	NO
5.	Do you suffer, or have you ever suffered from, high/low blood pressure?	YES	NO
6.	Has your doctor said that you have a condition and that you should only do physical activity recommended by a doctor?	YES	NO
7.	Have you had a cold or feverish illness in the last 2 weeks?	YES	NO
8.	Do you ever lose balance because of dizziness, or do you ever lose consciousness?	YES	NO
9.	Do you suffer, or have you ever suffered from, respiratory disorders? e.g. Asthma, bronchitis etc.	YES	NO
10.	Are you currently receiving advice from a medical advisor i.e. GP or Physiotherapist **not** to participate in physical activity because of back pain or any musculoskeletal (muscle, joint or bone) problems?	YES	NO
11.	Do you suffer, or have you ever suffered from diabetes?	YES	NO
12.	Do you suffer, or have you ever suffered from epilepsy/seizures?	YES	NO
13.	Do you know of any reason, not mentioned above, why you should not exercise? e.g. Head injury (within 12 months), pregnant or new mother, hangover, eye injury or anything else.	YES	NO

Nb. Participant must answer no to questions 3-13 to be deemed as healthy.

Signature of Participant : ………………………………… Date : …………………..

Name of Supervisor : …………………………………

Signature of Supervisor: …………………………….…. Date : …………………....

18.0 Appendix IX Chapter six informed consent form

ROBERT GORDON UNIVERSITY ABERDEEN

Informed Consent Form

SRRG Ref No:	SHS/15/23
Title (short):	The effect of climb assist on the demands of ladder climbing
Researcher	Peter-James Barron

	Please initial each box
1. I confirm that I have read and understand the participant information sheet dated 15/07/15 for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily.	
2. I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason.	
3. I understand that data collected during the study will be looked at by individuals from Robert Gordon University where it is relevant to my taking part in this research. I give permission for these individuals to have access to the data.	
4. I agree to take part in the above study.	

Participant:	
Name:	
Signature:	
Date:	

Person taking consent:	
Name:	
Signature:	
Date:	

Two copies to be completed one for the researcher and one for the participant

Informed consent September 2014

19.0 Appendix X Chapter seven participant information sheet

ROBERT GORDON UNIVERSITY ABERDEEN

SRRG reference number: SHS/16/11

27th September 2016

Study Title: An analysis of ladder climbing

Introduction.

My name is PJ Barron and I am a PhD student at Robert Gordon University. As part of my PhD I am undertaking a study to analyse ladder climbing from the perspective of climbing wind turbines, as routine maintenance requires. There is currently a lack of research relating to vertical ladder climbing which the turbine towers contain, and the role of wind turbine technicians. The study aims to enhance knowledge of the energy cost of ladder climbing, the effect of carrying a load when climbing and the effect of a space constraint when climbing imposed by current turbine designs. This will generate a physiological and biomechanical understanding which are strongly relatable to this industry's workforce.

We are inviting male and female participants to take part in this research. We are recruiting healthy males and females between the ages of 18 – 60 years to take part in this study.

Taking part in the study.

For this study we will be asking participants to come to the Sir Ian Wood Building (SIWB) at Robert Gordon University on 3 occasions; once for familiarisation and twice for testing on the ladder ergometer. Each session shall last no longer than 1 hour.

Familiarisation session

For the familiarisation session you will be asked to read the participant information sheet and have the opportunity to ask the researcher or supervisor any question relating to the study. At this point you will be asked to complete an informed consent form. You will then be seated for five minutes before having your blood pressure measured and recorded. You will then change into comfortable sports clothing before having your height measured. Changing accommodation is available within the laboratory facility. Based on this you will be given a climbing harness to wear. You will then climb for 5 minutes at a rate of 7.58 m per minute and then take a 5 minute break. You will then climb for another 5 minutes at the same rate to ensure you are familiar with climbing on the ergometer. At this point the familiarisation session will be completed and you will be asked to schedule in the two testing sessions with a minimum of 48 hours between each session.

For both testing sessions you shall have 5 reflective markers placed on the left hand side of your body prior to climbing. These will be stuck to your skin and are plastic and reflect light to be detected by the video camera (Hypoallergenic adhesive tape is available). These are to enable a video camera to detect your joint centres and specific landmarked positions, when filmed from the side.

Measurement session 1

In this session you will have your height and weight measured and recorded. You will be asked to sit in the bod pod (See image below) for about 3 minutes while the bod pod assesses your body composition. For this you will be required to wear your own swimming trunks, or alternatively be provided with form-fitting shorts (worn over underwear). (Female participants must wear a sports top and shorts, or one-piece swimwear).

Once completed, you will be asked to change into your own shorts, t shirt or vest, training shoes and wear a chest strap in preparation for climbing. A vest top is the preferred instead of a t shirt if possible. You will then warm up for 5 minutes at a vertical climb rate of 7.58 m per minute. You will then have the 7 markers placed on the left hand side of your body before fitting the climbing harness. At this point you will be fitted with a mask over your mouth and nose to measure the oxygen you consume and the carbon dioxide you breathe out. You will complete 3 bouts of 5 minutes of ladder climbing at 7.58 m per minute with 5 minutes recovery. Each of these climbs will either be with no load or a load of 5 kg or 10 kg in a climbing bag with the order being defined on the day. You will be required to wear the climbing harness, heart rate monitor strap and a mask over your mouth and nose until all testing is completed.

On the second measurement day you will again have your height and weight measured and recorded. As well as these measurements a number of bone length and body breadths shall be measured such a shoulder breadth and lower leg length. These measurements will be taken using a metal caliper and the measurement taken by the researcher. A 5 minute a warm up on the ladder ergometer with a heart rate monitor fitted will then be undertaken. Once the warm up is complete you will have the same 5 markers placed on the left hand side of your body before having the climbing harness fitted. You will then complete 5 minutes climbing at 7.58 m per minute. After 5 minutes the ladder ergometer will stop and you will be asked to freeze in position whilst a 3D scan of your climbing position is acquired using an iSense scanner via an iPad. This scan will take between 10 – 20 seconds with the researcher walking around you with the iPad camera focused on you to gather the scan data. You will then have 5 minutes recovery before completing 3 more bouts of climbing and scanning. For these, a vertical panel will restrict the available space for climbing to reflect the shape of wind turbine towers. The horizontal distance to the wall panel will be 1.22, 1.03 and 0.88 m for the three trials.

If you agree to participate, we will ask you to come to the research lab in SIWB at a mutually suitable time for a familiarisation session. We will then ask you if you have any further questions about the study and ask you to sign two consent forms for your participation. You retain one copy and I shall keep the other.

You are eligible to take part in this study if you are:

- Male or female, between the ages of 18 – 60 years.
- Apparently healthy at the time of measurement

You are not able to take part in this study if you:

- Have had an injury within the past 6 months or have persistent pain from a previous injury
- Have had a cold or fever within the past 2 weeks
- Take medication which affects their heart
- Are or have a chance of being pregnant
- Suffer with epilepsy or seizures
- Have uncontrolled or poorly controlled asthma

- Have had an asthma attack within the past 12 months
- Have uncontrolled or poorly controlled diabetes
- Suffer or have previously suffered from cardiovascular disorders? E.g. Chest pain, heart trouble, high cholesterol or COPD
- Suffer with a severe visual impairment
- Have a neurological condition
- Have a joint condition. E.g. Osteo or Rheumatoid arthritis.
- Have been told by a health professional not to undertake physical activity
- Have a clothed body mass greater than 105 kg
- On the day of testing have a blood pressure values greater than 140 for systolic and 90 for diastolic
-

At the end of the study we will send you a summary report of the research.

No payment will be offered for your participation.

You may withdraw from the research at any time without giving a reason.

Advantages to participating
There will be no direct advantage to you for participating in this research. The findings will add to our current knowledge of the physiological demands of climbing on a ladder ergometer. This research may inform the practice of the wind energy industry as currently very little is known about the demands of the role. The findings from this may in the future be used to inform the potential change in a physical employment standard for the industry,

Disadvantages to participating
There is a possibility of transient muscle soreness if you are not used to exercising in this way but you will not be at any greater risk than that of performing other forms of exercise. This possibility will be reduced by ensuring that you complete the warm up exercise. No other disadvantages are foreseen.

Confidentiality and anonymity
All the data we collect from you will be anonymised i.e. your name will not be able to be linked to the measurements or diary entries. In addition, your participation in this study will be confidential and we will not disclose the names of our participants. Your data will be securely stored on a password-protected computer within the requirements of the Data Protection Act (1998). Study data will only be seen by the researcher and their research supervisors. Analysed data will be presented in a research report and paper but no one will be able to identify individuals from this. Any images used will have the faces of participants obscured.

Any questions?
If you have any questions please contact PJ Barron (researcher) or Dr Arthur Stewart (research supervisor) at the address below.

What happens if there is a problem?
Please discuss any problems with me or my supervisor. Our contact details are given at the bottom of this letter. If you have a complaint please send details of this to the convenor, School of Health Sciences Research Review Group, Robert Gordon University, Garthdee Road, Aberdeen AB10 7QG k.cooper@rgu.ac.uk or Mrs Elizabeth Hancock, Head of School of Health Sciences, Robert Gordon University, Garthdee Road, Aberdeen AB10 7QG l.hancock@rgu.ac.uk

What will happen to my research data?
A research report and paper will be written as part of my PhD and may be more widely disseminated in academic and professional journals and conferences. The data we collect will be anonymised and confidential as well as being held in accordance with the RGU 2015 policy on data retention. Therefore the data will be assessed after a period of time for retention and kept if the data holds potential for future research to be conducted with it.

What happens now?
Please feel free to discuss this letter with your family and friends. If, after consideration, you would like to take part in this study or would like further information, please contact PJ Barron at the address below.

Thank you for taking the time to read this letter.

Researcher: PJ Barron PhD Student Institute of Health and Welfare Riverside East Robert Gordon University Garthdee Road Aberdeen AB10 7GJ Email: p.barron@rgu.ac.uk	Research Supervisor: Dr Arthur Stewart Institute of Health and Welfare Riverside East Robert Gordon University Garthdee Road Aberdeen AB10 7GJ Email: a.d.stewart@rgu.ac.uk Tel: 01224 262551

20.0 Appendix XI Informed consent form for chapter seven

Consent Form

SRRG reference number: SHS/16/11

Study title: An analysis of ladder climbing

Name of Researcher: Peter James Barron

Please initial box

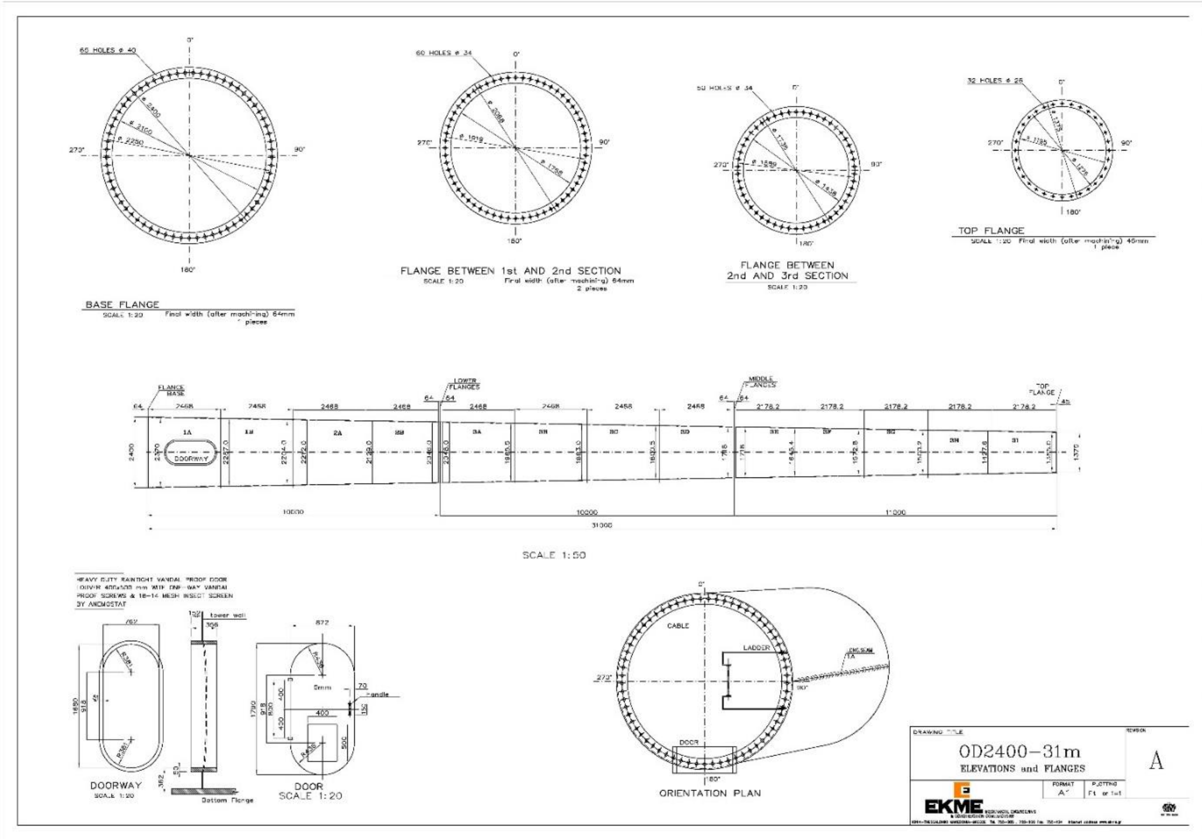
1. *I confirm that I have read and understand the information sheet dated 27/09/16 for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily.*
2. *I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason.*
3. *I understand that data collected during the study will be looked at by individuals from The Robert Gordon University where it is relevant to my taking part in this research. I give permission for these individuals to have access to the data.*
4. *I agree to having video recording taken throughout the testing session and agree to a body scan being taken also for research purposes*
5. *I understand that photographic and video data is collected and once anonymised used in publications, written works and publicity.*
6. I agree to anonymised images from my testing session being used in any research output (e.g. academic articles, professional papers, conference presentations) from this study.
7. *I agree to take part in the above study.*

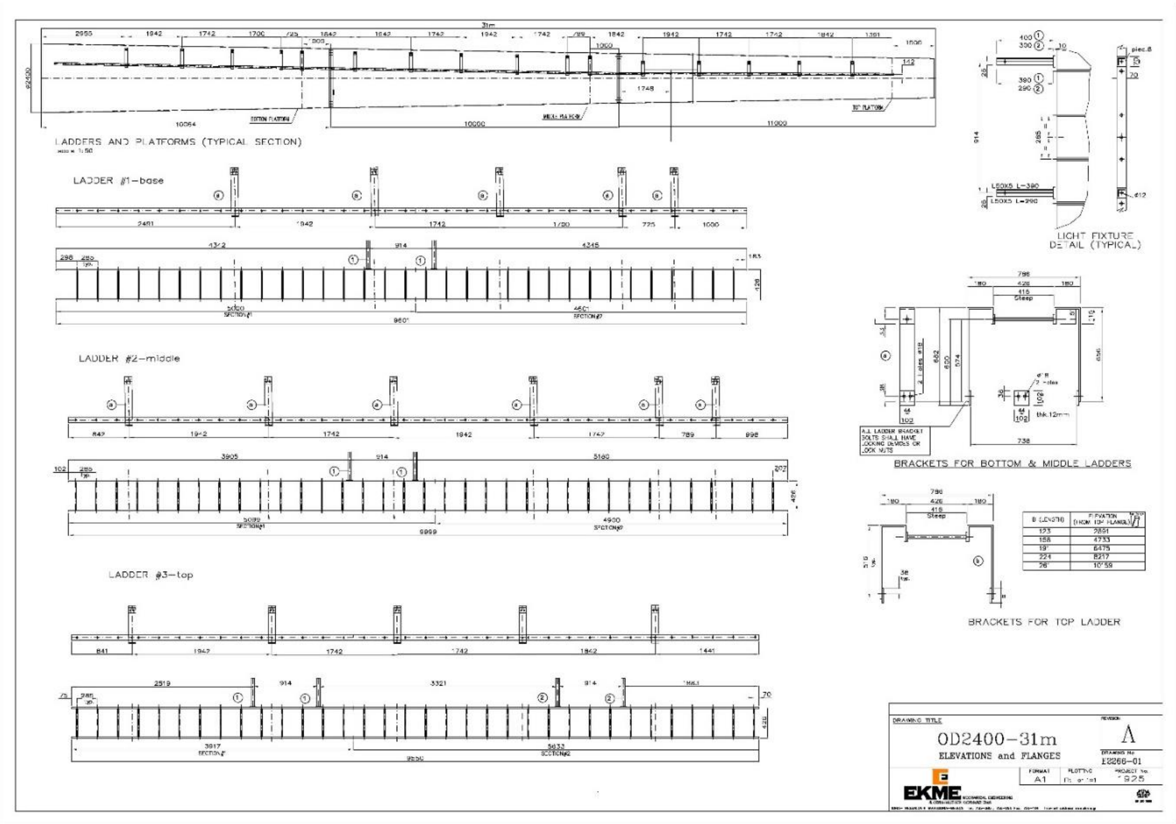
Name of participant *Date*
Signature

Name of person taking consent *Date* *Signature*

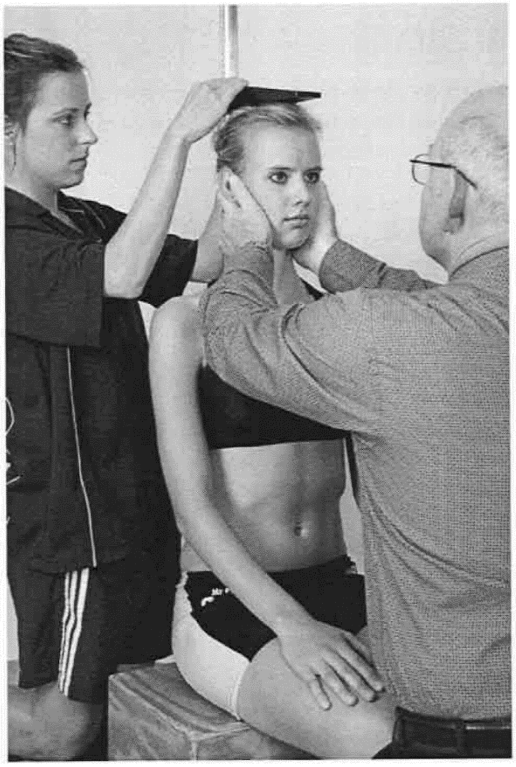
Two copies to be retained: one for researcher and one for participant.

21.0 Appendix XII Wind turbine schematics





22.0 Appendix XIII Images of breadths, heights and length (Stewart et al., 2011)



3 Sitting height

Definition: The perpendicular distance between the transverse planes of the Vertex® and the inferior aspects of the buttocks when seated.

Equipment: Stadiometer

Method: The preferred technique is the stretch stature method. The subject is seated on a measuring box or level platform. The hands should be resting on the thighs. The subject is instructed to take and hold a deep breath and while keeping the head in the Frankfort plane the measurer applies gentle upward lift through the mastoid processes. The recorder places the head board firmly down on the Vertex®, compressing the hair as much as possible. Care must be taken to ensure the subject does not contract the gluteal muscles nor push with the legs.

Note: Repeated measures should be taken as near as possible to the same time of day as the original measurement. The time of measurement should be recorded on the proforma.

s

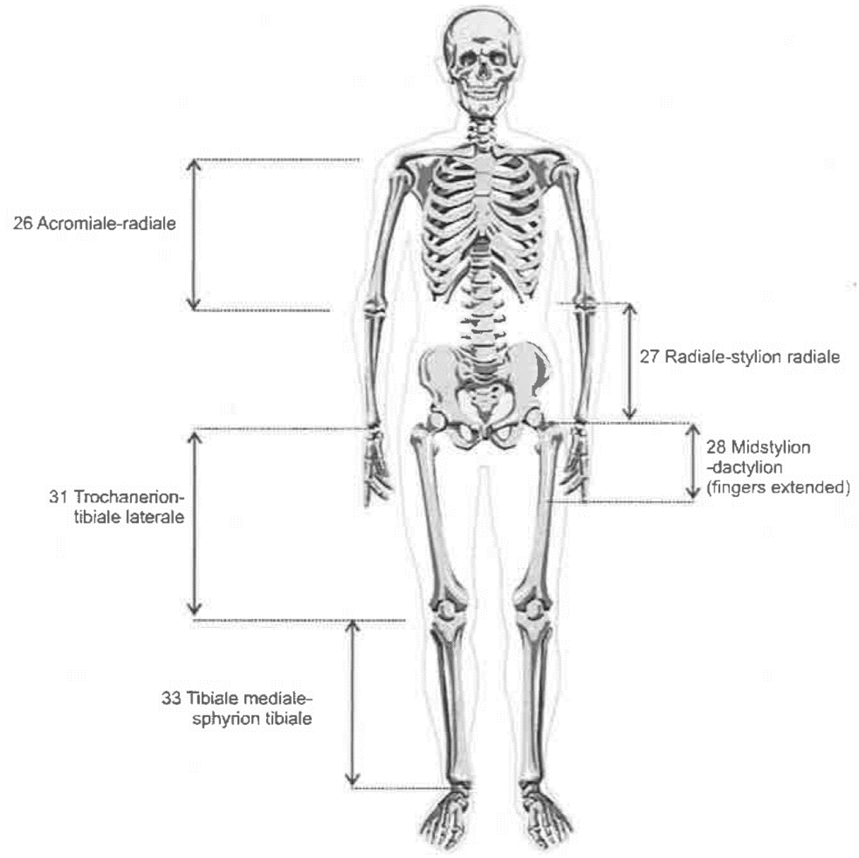


Figure 63: Direct lengths. Note that all measurements are normally taken on the right-hand side of the body, and perpendicular to the long axis of the limb

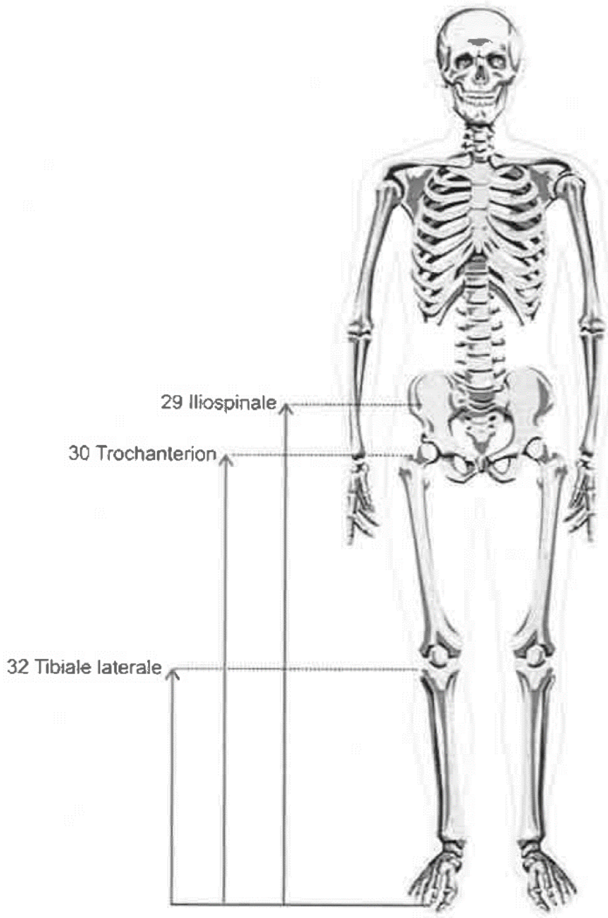


Figure 62: Projected lengths

Figure 75: Biiliocristal breadth

36 Biiliocristal

Definition: The linear distance between the most lateral points of the iliac crests. (*Note*: This is not the same as the iliocristale, which is on the mid-axillary line).

Subject position: The subject assumes a relaxed standing position with the arms across the chest.

Method: The measurer stands in front of the subject and the branches of the anthropometer are kept at approximately 45° pointing upwards. Firm pressure is applied by the anthropometrist to reduce the effect of overlying tissues.

7.2 Breadth Measurements

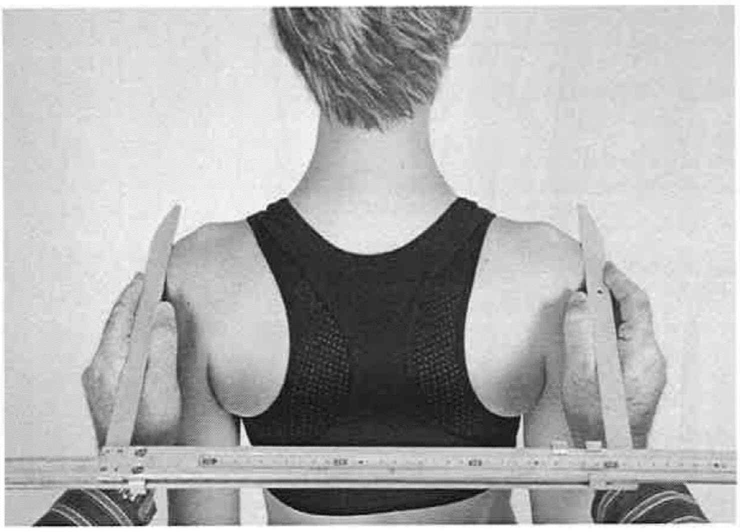


Figure 73: Biacromial breadth

34 Biacromial

Definition: The linear distance between the most lateral aspects of the Acromion processes.

Subject position: The subject assumes a relaxed standing position, with the arms hanging by the sides.

Method: This distance is measured with the branches of the large sliding caliper placed on the most lateral surfaces of the acromion processes (below the marked Acromiale® landmark). The subject stands with the arms hanging at the sides, and the measurer, standing behind the subject, should bring the caliper branches in to the acromion processes at an angle of approximately 30° pointing upwards. Pressure should be applied to compress the overlying tissues, but should not move the shoulders. The measurement is taken at end tidal expiration.

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