THE INTERACTION OF FATIGUE AND LOAD ON REACTION TIME AND DECISION-MAKING DURING AN AFFORDANCE-BASED TASK

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The process by which an athlete is attuned to their affordances for action in a given environment is known as perceptual-motor calibration. However, given that athletes operate in dynamic, fluid environments, they must be able to recalibrate to account for perturbations, such as fatigue or load carriage. **PURPOSE:** To examine the independent and interactive effects of low intensity to fatiguing exercise and load carriage on perceptual-motor calibration **PROCEDURES:** 23 participants (Age (yrs) = 25.26 ± 3.26) completed an incremental fatigue protocol, with stages of low, moderate, high, and fatiguing intensities, on two separate occasions (loaded/unloaded). At baseline and the end of every stage, subjects made perceptual-motor judgements for maximal jump distance, and the accuracy of judgements (ACC) and reaction time (RT) were calculated. 2x5 ANOVAs, or nonparametric equivalents, were utilized to test for mean differences in ACC and RT across exercise intensity and load carriage conditions. **RESULTS:** No interaction of exercise intensity and load carriage was detected, or main effect of load carriage. A main, quadratic effect of exercise intensity was detected on RT ($F = 18.587$, $p < 0.001$), with RTs decreasing through the moderate stage (Mean Difference (ms) = -38.25) and increasing through post-fatigue (Mean Difference (ms) = 38.817), however no effect was detected on ACC. **CONCLUSIONS:** The results indicate that exercise has a significant effect on perceptual-motor calibration, with improvements through moderate intensity exercise, and decrements with higher intensities,

necessitating recalibration. However, load carriage appears to not have a significant impact on perceptual-motor calibration.

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INTRODUCTION

The broad classification of "ecological" theories of movement control are rooted in the relationship between a person's perception of a situation and their resulting action, framing this relationship as a symbiotic, ongoing process that directs movement.[1,2] Under this framework, individuals adjust and re-adjust their actions based on the changing environment, stimulus energy (e.g., light, pressure, chemical energy, sound) relevant to the task or action at hand, and information obtained from previous actions of a similar nature.[3,4] Under an ecological theory of movement control, Gibson[5] developed the concept of affordances. Having since grown and expanded in its definition and application, affordances have been central to the application of ecological theories to real-world situations.

Gibson[5] first described affordances, in 1966, as opportunities for action provided by the environment. Expanding upon this, Fajen et al.[3] described affordances in terms more relatable to occupational (military, firefighters, police) and competitive athletes, as the abilities in a given environment or situation that allow for a successful action by an individual. Related to affordances, *action boundaries* can be defined as the limits of a given movement for an individual within a set of environmental constraints.[3,6] Operationally, action boundaries can be thought of as the maximum height or distance a person is capable of jumping or the maximum length a person is capable of reaching. *Action capabilities*, then, can be defined as the set of characteristics possessed by an individual that determine their action boundaries.[3,6]

One important application of affordances lies in attuning an athlete to their opportunities for action in a given environment, serving to improve motor control and decision-making in future situations.[3] This attunement is often referred to as *perceptual-motor calibration*, defined by Van Andel et al.[7] as the process by which an individual scales their perception of their action boundaries to their action capabilities. Previous research has demonstrated the effects of disrupting environmental/task constraints or an individual's action capabilities, on limiting the accuracy of action boundary judgement and increasing reaction times.[8-14] What's more, this work has established that these disruptions can also have profound effects on movement strategies and postural control.[8-14] In the case of a disruption to an individual's action capabilities, the need for *re-calibration* arises, where an individual is required to re-scale their perceptions of their action boundaries in proportion to the change in their capabilities (model depicted in Figure 1 below).[10]

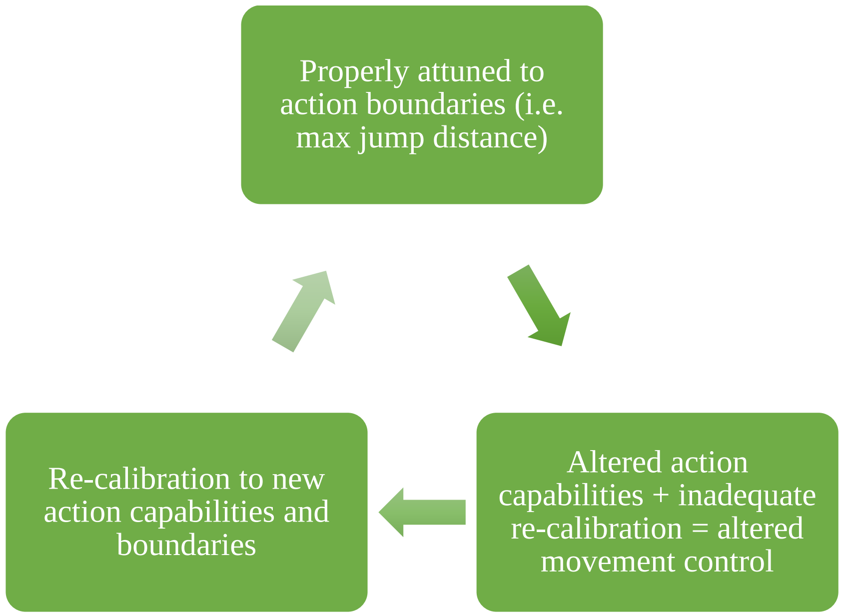

Figure 1: Model of perceptual-motor recalibration

Research demonstrating the effects of perturbing a movement system through the disruption of action capabilities provides a basis for further application of perceptual-motor calibration in occupational and competitive athletes. This body of work demonstrates that affordances are important in the prospective control of movement and that manipulations to action capabilities can have a profound effect on decision-making and perceptual-motor control. However, much of this research has focused on artificial manipulations of action capabilties (i.e. altering bat weight or providing incorrect visual information), where the perturbations to movement control were not normal or naturally occuring variations in action capabilities.[10,11] Further, one study focused on the effects of total sleep deprivation, a manipulation that is not relevant to most athletes.[12] Two variables that may have more direct application in studying the impact of inadequate perceptual-motor re-calibration are fatigue and load carriage.

Fatigue can be defined, as described by Abbiss[15], as feelings or sensations of tiredness, resulting in decrements in muscular performance and physical function. Fatigue and fatiguing exercise are of particular interest in the sports medicine field, as they are thought to create an environment where the risk of musculoskeletal injury is higher and decrements to performance are likely to occur. [16-19] While much of the research on exercise and fatigue has focused on neuromuscular variables, a wealth of research has also identified impairments to cognitive and, to a lesser-degree, psychomotor performance related to exercise-induced fatigue.[20-26] Additionally, work focusing on the effects of sub-maximal exercise have shown a positive effect of exercise on cognitive performance through moderate to high intensities, with a threshold reached at higher intensities and further increases in intensity resulting in decrements to performance. [23,27-31] Given that high intensity exercise is a common demand of competitive sport and for occupational athletes, the relationship between exercise intensity and perceptual-motor calibration is also applicable for these populations.

Research on exercise and cognitive performance suggests that cognitive control of movement is impaired during exercise at high intensities as a consequence of fatigue. However, the majority of this research has focused on cognitive or psychomotor performance measures that are not aligned with an affordance-based perspective of movement control, utilizing simple reaction time measures with a limited motor component, tasks without a decisional component, or tasks with a decisional component that is not action-scaled. An action-scaled affordance is one which is scaled, predominantly, to an individual's action capabilities (strength, power, endurance), making it more relevant to the demands of a dynamic, athletic environment. Few studies have assessed the effects of fatigue on performance on an action-scaled task and no previous research has assessed the effects of sub-maximal exercise intensities to establish if the same threshold for performance occurs at a given intensity of exercise.[13] It may be that the same "arousal" effect that is seen with cognitive performance measures does not hold for action-scaled tasks, where the perceptual-motor abilities are tested in comparison to simple reactionary abilities.

Another variable that may affect the accurate perception of affordances is load carriage. Load carriage is a daily necessity for occupational athletes across many sectors of public service, most notably in police, firefighter and military personnel.[32-34] While loads can be carried externally, many of these are body-borne or worn on the body. [32-34] Body-borne loads can range from personal protective equipment (PPE), such as body armor and helmets, to self-contained breathing apparatuses carried by firefighters.[32-34] Load carriage is a topic of interest in sports medicine research, given its negative effect on operational mobility and high levels of physiological/biomechanical stress associated with MSI.[33,35-38] What is more, body-borne loads contribute significantly to the onset of fatigue during operational activities by increasing the workload for an individual, and thereby, the effective intensity of physically demanding activities.[35,36]

For occupational and competitive athletes, fatigue and load carriage are highly relevant aspects of movement control, that may affect both performance and injury risk. However, a limited amount of work has been dedicated to studying the effects of these two variables on movement control and decision-making during an action-scaled task.[8,13,14,39] Even within this limited work, studies have utilized tasks that are not transferrable to a wide population of occupational and competitive athletes (i.e. marksmanship or stepping over/under a hurdle).[8,13,14]

Finally, previous literature has focused on the separate effects of fatigue and load, with no studies capturing the interactive effects of these two variables on perceptual-motor calibration. Given the previously demonstrated contributions to fatigue with the addition of load carriage, addressing this interaction is key in delineating whether the presence of load carriage, fatigue or a combination of both have the greatest impact on perceptual-motor recalibration. [35,36] Therefore, the purpose of this study was to examine the independent and interactive effects of fatigue and load on perceptual-motor recalibration using a task rooted in an affordance-based theory of movement control. A secondary purpose was to investigate the effects of sub-maximal exercise, through the onset of fatigue, on this same task.

1.1 SPECIFIC AIMS

Specific Aim 1: To establish the effects of fatigue and load carriage on reaction time and the ability to accurately judge action boundaries during a double-legged, horizontal jump.

Hypothesis 1a: Reaction times will increase and judgement accuracy will decrease in response to both fatigue and load carriage.

Hypothesis 1b: Fatigue and load carriage will show an interactive effect, with reaction time higher and action boundary judgement accuracy lower compared to isolated conditions of fatigue or load carriage.

Specific Aim 2: To establish the effects of increasing exercise intensity on reaction time and the ability to accurately judge action boundaries during a double-legged, horizontal jump.

Hypothesis 2a: Reaction times will show an inverted U-shaped pattern with increasing exercise intensity, with a threshold at approximately 60-70% of maximal intensity (defined by heart rate reserve), after which, reaction times will increase.

Hypothesis 2b: Judgement accuracy will improve with increasing exercise intensity with a threshold at approximately 80-90% of maximal intensity, after which, accuracy will decline.

1.2 SIGNIFICANCE

The proposed research addresses the identified gaps in affordance-based research, providing evidence on the relationship between fatigue, load carriage, and affordance judgement. The results of this study will provide evidence on the application of fatigue and load carriage in perturbing or challenging perceptual-motor calibration. In normal humans, perceptual-motor judgments are highly accurate, with most perturbations to action capabilities producing modest decrements, if any. However, given the significant impact of fatigue and load carriage on cognitive and physical performance, it may be that the wrong perturbations have been employed. Summarily, it may be that fatigue and load carriage are modes of perturbation by which perceptual-motor calibration can be truly challenged.

Results of the investigation will provide direction for trainers and sports medicine clinicians working with this population in relation to the changes in perceptual-motor acuity related to either fatigue, load carriage, or both. Further, it will provide information on the specific intensity of physical activity that these changes might cause. The intensity an individual is exercising or working at, as measured by heart rate response, is relatively easy to track with current technology. Subsequently, the results of this study can be applied in allowing clinicians to track the periods of competitive play or operational activities when their athletes are at or above the thresholds where perceptual-motor calibration is perturbed, and intervene to limit subsequent performance deficits.

2.0 REVIEW OF LITERATURE

2.1 AFFORDANCES: BACKGROUND AND APPLICATION

2.1.1 Defining Affordances

The concept of affordances has evolved since its first description by Gibson[5] as opportunities for action provided by the environment of an animal. Gibson[5] defined the environment relative to the behaviors or movements that it allowed for an animal. In an attempt to further define affordances in more ontological, "realist" terms, Turvey[40] described affordances as, dispositional properties of the environment that are complemented by dispositional properties of animals, termed "effectivities". In contrast, Stoffregen[41] defined affordances as "emergent properties of animal-environment system (pg. 116)", arguing that the properties of the environment cannot be separated from those of the animal, as would be suggested by Turvey's definition.

Finally, Fajen et al.[3] defined affordances in terms relevant to the application of this concept to athletes as, "properties of animal-environment systems that can be specified in patterns of stimulus energy and that can therefore be directly perceived (pg. 90)". This definition, firstly, frames affordances as properties of the animal-environment system, where an afforded or non-afforded behavior is equally dependent on the characteristics of the surrounding environment and the individual acting in the environment. In a simple example, the affordance for climbing, or stepping onto, a set of stairs is equally dependent on the characteristics of the stairs (density of material, slope/riser height of stairs) as it is on the characteristics of the individual who would be climbing them (body mass, leg height/strength/flexibility).[41,42] An important qualifier for this model of perceptual judgements is that basic motivational variables are held constant, or in other words, the only variables an individual is considering are the physical characteristics of the stairs and themselves. Further, the specific behavior in question is stepping, or reaching up with the leg and pushing oneself onto the stair, as there are a number of behaviors a person could adopt to climb a set of stairs that did not afford stepping.

Second, it describes the method by which affordances are perceived, through patterns of stimulus energy (i.e. light, sound, touch).[3] Using the previous example, in deciding whether a set of stairs affords stepping, an individual must accurately perceive the relationship between their own characteristics and those of the stairs in order to correctly judge their "climbability". This information can come from an array of information, from previous exploration of similar situations to visual, somatosensory and vestibular information. Finally, Fajen's definition describes the perception of this information as "direct".[3] This is in contrast to theories that maintain that our perceptions of the environment in which we act are indirect, meaning that they are merely interpretations of the stimulus energy we are receiving.[3] As Fajen et al.[3] point out, indirect theories of perception have been used in the past successfully, but more so in describing failures of perception or illusions. In applying affordances to sport and occupational scenarios, a theory of perceptual-motor skill that is based on illusions would not seem applicable.[3]

In summary, the definition of affordances by Fajen et al.[3] would seem to encapsulate the improvements in affordance theory since the first description by Gibson[5] fifty years ago. It captures the reciprocal nature of affordances as properties of both the environment and the actor. This is critical, given that for an individual moving in an athletic or operational environment, successful decision-making is dependent on their ability to integrate stimulus energy informing on the properties of the environment with that informing on their current physical and mental capabilities.

Further, it describes the method by which these judgements are made by occupational and competitive athletes, by directly perceiving these internal and external characteristics through an array of stimulus energy.

2.1.2 Affordance-based Assessments: Action Capabilities and Action Boundaries

An athlete must be able to accurately judge their affordances in relevant situations. [27, 28, 62] This ability is often tested by assessing a person's judgments about the limits of their physical capabilities (action capabilities), and therefore, the limits of their possible actions (action boundaries). [27, 28, 62] Action boundaries can be defined as the limits of a given movement for an individual within a set of environmental constraints.[3,6] Action capabilities can be defined as the set of characteristics possessed by an individual that determine their action boundaries.[3,6] Using these operational definitions, a plethora of previous research has identified important experimental considerations related to affordance-based assessments. [12,43-48]

Body-scaled affordances are those where the possibility for action is mainly determinant on the interaction between environmental properties and some combination of anthropometric properties (arm/leg length, height, weight, etc…).[3] Action-scaled affordances are those which are more constrained by the interaction of an individual's action capabilities (strength, flexibility, motor coordination, etc…) and the surrounding environment. [3] Action-scaled affordances are, therefore, often transitory or fluid, whereas body-scaled affordances are more rigid in nature, at least in the short-term. The distinction between action-scaled and body-scaled affordances is important, because while previous research has demonstrated that individuals are able to perceive their action boundaries with high accuracy for body-scaled affordances (i.e. step-on-ability, sit-on-ability), tasks that are predominantly action-scaled have shown more variability.[13,43,44,48-58]

In a study by Cole et al.[48], accuracy of action boundary judgements was measured for a number of action-scaled and body-scaled affordances. It was found that action-scaled affordances (leaping, swinging) showed significantly higher errors in accuracy compared to body-scaled affordances (stepping, reaching).[48] The authors hypothesized that it is the launching nature of these action-scaled tasks, leading to a larger number of variables that must be properly integrated into judgements, that may account for the decrease in accuracy of judgements.[48] This effect has been demonstrated by a number of other studies, most notably a series of studies by Ramenzoni et al.[43] and Pepping and Li[58] utilizing similar tasks.[57] In these two studies, participants were asked to judge their action boundaries for either maximum reach height or maximum jumping-reach height.[43,58] Both found significantly lower errors in judgements of maximum reach height compared to jumping-reach height, similar to those reported in the study by Cole for stepping compared to leaping.[43,58]

To the contrary, several studies have reported highly accurate judgements for action-scaled affordances.[13,49,54,55] A study by Day et al.[49] mirrored the tasks used by Cole et al.[48], assessing action boundary judgements for maximum stepping and horizontal leaping distance. The authors reported equivocal accuracy in judgements for both tasks, with some results showing a trend towards better accuracy in judgements on leaping ability.[49] These results, as well as those of other studies, put in doubt whether action-scaled and body-scaled tasks differ with respect to accuracy of judgments about action boundaries. However, at the very least there is some evidence that this distinction is necessary when discussing affordance-based research.[43,48,58] Further, it would seem that the ability to judge action-scaled affordances, where the affordance primarily depends on an individual's action capabilities, is particularly relevant in assessing an athletic population.[3]

Another aspect of affordance-based measures established in previous research is related to the mode of judgement. Many previous studies have used verbal judgements of action boundaries, where participants are asked to verbally select or confirm when a given marker is at the limits of their action capabilities.[12,14,39,44,45,48,49] However, action-based judgements, where movement is allowed in the assessment of the action boundary, generally improve response accuracy and speed.[55,56,58-60] Oudejans et al.[62] demonstrated this using a task requiring participants to judge the catchability of a ball under two conditions; one where they were required to remain stationary and another where they were allowed to move for a short period of time with the ball, as if to catch it. The authors reported better judgements under the movement condition, even though participants only moved with the ball for 1 second before making judgements.[62] In a different experimental set-up, Pepping and Li[58] assessed differences in reaction time and judgement accuracy on a reaching and jump-reaching task based on whether participants were asked to verbally assess their action-boundaries or actually reach or jump and reach when they thought a boundary was reachable. They found that while accuracy of judgements was similar between conditions, reaction times were significantly shorter for both tasks when subjects were required to perform the movement as part of their judgements.[58]

One study has presented evidence contradictory to these findings.[56] Fajen et al. [56] attempted to replicate the findings of the study by Oudejans, utilizing a similar task but one performed in a virtual reality environment. While the authors reported no effect of movement on the accuracy of action boundary judgements, the results of the study do show a similar trend to those reported by Oudejans.[56] What is more, a number of limitations are present in the study by Fajen et al. [56] , most notably the fact that it was conducted in a virtual reality environment.[56] Among other issues, this presents the likelihood that participant's movement may have been restricted or altered because of unfamiliarity with the environment, leading to alterations in judgement during the movement condition.[56]

Coupled with the fact that the study by Fajen does not address the results presented by Pepping and Li[58] and others regarding delayed reaction times, it would seem that previous research has identified the need for a movement-based judgement task, compared to a simple verbal assessment.[59,60] In essence, it is important that the link between perception and action is maintained when assessing judgements of affordable and unaffordable actions.[58] From a practical standpoint, this would also seem to be a more applicable assessment for an athletic population. As noted in a review by Fajen et al.[3], preceding their study, affordances in a fluid, sport or operational environment are dynamic, where an action may be afforded one moment and gone the next. Therefore, it would seem that an affordance-based measure meant for application in this context should encapsulate the ability to both judge a given action boundary and coordinate the necessary action, including the temporal structure/limitations at which these occur.

Previous research has identified an intuitive relationship between accuracy and initiation times related to judgements, and the closeness of the presented stimulus to the actual action boundary.[58,59,61,62] In one of these studies, Smith and Pepping[46] described a task requiring individuals to judge whether a virtual ball would fit through virtual apertures of varying sizes. As would be expected, a quadratic relationship was observed between reaction times and the ratio of size of the aperture to the size of the ball, peaking at a ratio equivalent to the percieved action boundary.[46] In other words, as the size of the aperture approached the minimum size that would allow the ball to pass through it (the action boundary), reaction times increased.[46] Further, as the aperture size approached the extremes of affording (largest) or not affording (smallest) the ability to pass the ball, reaction times decreased.[46]

From a practical standpoint, Smith and Pepping[46] demonstrate that performance on affordance-based measures exists on a continuum relative to the action boundary that is presented to an individual.[54, 69, 85, 86]. In the study by Smith and Pepping[46], the mean perceived action boundary was at approximately 2-9% of the actual action boundary. This means that even within a fairly small range of an individual's action boundary, significant differences in reaction times can occur. Therefore, it would seem that for an athletic population, where the occupational demands necessitate quick and accurate decision-making, the presentation of gaps in close proximity to an individual's action boundary are more likely to delineate between differing levels of perceptual abilities. Further from the action boundary, it is likely that reaction times will even out and represent more of a simple reaction time measure as the difficulty of judging the gap becomes too routine for an athletic population.

In summary, several considerations for the implementation of affordance-based measures have been discusssed, with a focus on considerations for an athletic population. Occupational and competitive athletes require an affordance-based measure that is action-scaled, incorporating a movement-based decisional component or judgement, and focusing on the decision-making ability on gaps at or in close proximity to the individual's action boundary. Previous research has shown that body-scaled measures and measures only requiring a verbal assessment show differing patterns of response accuracy and reaction times compared to action-scaled measures and those requiring a movement-based decision. [13,43,44,48-58] Further, previous research has shown that judgements made in close proximity to an individual's action boundary are more likely to challenge perceptual-motor abilities. [63, 80, 98, 99] Finally, occupational and competitive athletes operate in environments that necessitate quick and accurate perceptual-motor judgements. As such, these considerations also focus on replicating this demand as closely as possible, as well as being rooted in previous literature.

2.1.3 Perceptual-motor Calibration

Central to the application of affordances and affordance-based measures to the occupational operating and athletic environments, as well as in others, is perceptual-motor calibration. Described by van Andel et al.[7], perceptual-motor calibration is the scaling of an individual's perception of affordances to their action capabilities, allowing for the distinction of possible and impossible actions in a given environment. The process of perceptual-motor calibration is facilitated by *perceptual attunement*, whereby an individual is trained to recognize the correct stimulus energy, from available perceptual information, that provides for a succesful movement behavior.[3,40] This concept provides immense opportunity for individual's working with occupational and competitive athletes in improving performance outcomes in real-world situations. Attuning an individual to their action capabilities in a relevant operational or athletic environment is conducive to the prospective selection of movement strategies, where an individual improves their ability to anticipate future affordances and thereby improve movement outcomes.[3] A number of studies have demonstrated this process of perceptual-motor calibration.[7]

The simplest form of perceptual-motor calibration can be viewed as a learning effect, where individual's improve their judgements of action boundaries on a novel task by interacting with the environment, often termed *exploration*.[43] Ramenzoni et al.[43] designed a study to assess the effects of exploration on action boundary judgements of maximum jump-reach height. Participants were required to make judgements based on a ball hanging overhead, on whether their action capabilities afforded jumping and touching the ball.[43] The authors reported a significant main effect of trial number across ten trials, where judgements steadily increased in accuracy until leveling off around the seventh trial.[43] In essence, participant's perceptions of their action boundaries were scaled closer to their action capabilities across successive trials. What's more, participants were not allowed to actually perform the jumping task across trials, simply giving verbal judgements as to whether the ball should be lowered or raised until they estimated it to be at their action boundary.[43] This means that this perceptual-motor calibration occurred without any information on their accuracy in previous trials or feedback from investigators.[43]

Two other studies have described successful calibration by means of an individual actually acting in the designated task.[49,63] Day et al.[49] investigated perceptual-motor calibration to action capabilities determining maximal horizontal jump distance and maximal stepping distance. After initial judgements were made for each task, half of the participants practiced each respective task by making an initial judgement again, and then performing the respective movement after all markers were removed from the floor by an investigator.[49] The author's reported significantly better judgements of action boundaries after practicing horizontal jumping.[49] Even more compelling, a crossover effect was noted whereby judgements for stepping also improved in the group practicing jumping.[49] No effect was noted in the group practicing stepping for either task.[49] A study by Franchak et al.[63] noted similar findings, where action-based practice was used to succesfully attune individuals to their action capabilities.

While these results are promising, the process of perceptual-motor calibration in real-world situations is a fluid one. For an athletic population, action capabilities are in constant flux due to factors affecting physical characteristics as well as those of the surrounding environment. Therefore, an individual must not only be able to calibrate to their inherent action capabilities, but re-calibrate based on changes to their inherent action capabilities. A wealth of past research has focused on the efficacy of re-calibration in response to changes in action capabilities.[12-14,39,44,64-68]

Pepping and Li[64] investigated the effects of manipulating a task constraint, ground surface, which in turn would affect an individual's action capabilities in a jump-reach maneuver. The investigators utilized a gymnastics springboard surface to enhance jump-reach height and a wrestling mat surface to impair jump-reach height.[64] Before trials, participants were allowed to interact with each ground surface for a short period (1 minute).[64] The results showed that participant's were able to adequately re-calibrate to the springboard surface, but systematically underestimated their action boundaries in the mat condition.[64] However, the mean absolute errors were equivocal between conditions.[64] In a second experiment, the investigators utilized three ground surfaces: a firm one (hardwood), a trampoline, and a sand surface.[64] The authors reported similar results to the first experiment, demonstrating a rapid re-calibration in perceptions to the altered action capabilities.[64]

Much of the past research has confirmed these results, demonstrating that re-calibration to altered action capabilities is possible and without much instruction.[13,39,44,65,67-69] In contrast, Daviaux et al.[12] investigated the effects of total sleep deprivation on the estimation of action boundaries for stepping over a hurdle. The author's found that judgement accuracy declined significantly with increasing sleep deprivation.[64] In another study, Petrucci et al.[14] examined the effects of wearing normal firefighting gear on the ability to judge action boundaries through several tasks (stepping over and under a hurdle, passing through a doorway). The author's reported significant errors in action boundary judgements while wearing gear, however no comparisons were made to a control condition, where judgements were made without gear.[64] Further, both of these studies, showing contradictory results compared to most previous research, have investigated body-scaled affordances.

While holding some limitaitons, the studies by Daviaux and Petrucci demonstrated a significant shortcoming in previous research addressing perceptual-motor re-calibration to changing action boundaries. The majority of this past research has demonstrated rapid re-calibration in response to predominantly artificial manipulations in action boundaries; manipulations that are not representative of the alterations to action capabilities experienced by occupational and competitive athletes. These manipulations included: altering height by placing blocks under the feet[44,68], increasing reach with the addition of a hand-held tool[69], or altering virtual walking speed comparative to actual speed[65]. In a normal operational or athletic environment, changing height or incorrect visual information about gait speed are not variables that have to be accounted for. What's more, the studies by Daviaux and Petrucci offer some evidence that the perceptual motor re-calibration may not be as rapid or effortless in response to variables that are experienced in these environments: sleep deprivation and additional body-borne loads.

In conclusion, past research has identified significant practical and theoretical bases for the concept of perceptual-motor calibration in attuning individuals to their action capabilities and improving decision-making during movement. [12-14,39,43,44,49,63-68] As described above, the process of perceptual motor calibration and re-calibration would seem to provide evidence for the application of affordance-based theory in improving performance outcomes in the occupational and competitive athlete population. However, in providing more concrete evidence of this application, research is needed into the effects of variables that are relevant to this population. As will be discussed in the following sections, fatigue and load carriage are two variables that would seem to be ripe for investigation in this effort.

2.2 FATIGUE

2.2.1 The Complex Systems Model of Fatigue

Fatigue can be broadly defined as "sensations of tiredness and associated decrements in muscular performance and function".[15] While the definitions of fatigue used by different disciplines generally follow this theme, models used to explain fatigue vary greatly, often focusing on the mechanisms of fatigue important to researchers in that discipline.[15] Several commonly described models are the: *Cardiovascular/Anaerobic Model, Energy Supply/Depletion Model, Neuromuscular Model, Muscle Trauma Model, Biomechanical Model, Thermoregulatory Model, Psychological/Motivation Model, and Central Governor Model*.[15,70] All of these models hold their own levels of evidence in establishing the development and onset of fatigue.[15,70] Consequently, a more current model of fatigue has developed under the assumption that neurological, muscular, cardiovascular, and metabolic systems all contribute (variously) to fatigue during physical activity.[71]

This interactive model is known as the *Complex Systems Model (*CSM).[71-73] Also referred to as a *non-linear* model, CSM differentiates from the aforementioned models that depict fatigue as a linear process.[71-73] In these former models, fatigue is proposed to occur at a certain intensity or duration of exercise, hence it can be studied in a linear fashion up until that set intensity and duration. Further, fatigue is proposed to occur because the intensity and duration of exercise is such that exercise above these thresholds causes a reaction or limitation of some sort, depending on the proposed model; in essence, a catastrophe. For example, the *Cardiovascular/Anaerobic Model* proposes that fatigue occurs at the point where the heart can no longer maintain cardiac output such that the necessary amount of oxygen is delivered to exercising muscle and metabolic waste is cleared from muscle and the bloodstream.[15,70] The *Energy Supply/Depletion Model* maintains that fatigue occurs when Adenosine Triphosphate (ATP), an exercising muscle's energy source, can no longer be supplied necessary quantities.[15]

As described by Lambert et al.[73], the CSM instead proposes that fatigue is a perceived sensation that results from an interaction of many complex physiological processes. In this model, the brain is considered to be the central processing center, receiving afferent sensory information regarding changes in physiological processes during exercise.[71,73] Further, the brain is the central regulatory center, adjusting feedforward and feedback control based on the acquired sensory information and signaling within the central nervous system (CNS) itself.[71,73] During exercise, this regulation of physiological processes by the brain, is an ongoing, dynamic process with the end goal of maintaining homeostatic conditions and signaling fatigue before these homeostatic conditions are irreparably altered. [71,73] In this sense, the CSM proposes that these complex systems work to avoid the types of catastrophes described by older models, where the definition of fatigue more closely matches that of complete exhaustion.[71,73] Since this model was first proposed by Ulmer[74], several key components necessary for this model to hold true have been demonstrated.

Firstly, numerous studies have demonstrated the central regulation of effort during exercise, demonstrating both feedforward and feedback control in response to changes in homeostatic conditions.[75-86] In a study by Amann and Dempsey[87], competitive male cyclists performed a number of cycling time trials; one in a rested state, and two after "pre-fatiguing" trials at incremental intensities (83% and 67% of maximum power output). To measure central motor drive, pre- and post-quadriceps potentiated twitch and maximum voluntary contractions were assessed using transcranial magnetic stimulation and electromyography. Further, continuous voluntary muscle activation was measured during each time trial. The authors reported a dose-dependent effect of pre-fatigue on time trial performance as well as voluntary muscle activation during each time trial. However, decreases in both quadriceps potentiated twitch and maximum voluntary contractions were identical between all conditions. These results present strong evidence that feedback from pre-fatigued muscle determined a feedforward mechanism in central motor drive to regulate skeletal muscle recruitment and force output in an attempt to limit further peripheral fatigue.[87]

In another study, Tucker et al.[82] examined the effects of cycling in hot compared to cool ambient conditions on time-trial performance, body temperature, skeletal muscle recruitment, and perceived exertion. It was found that power-output and skeletal muscle recruitment began to decrease after a mean of 30% of trial completion in the hot compared to cool condition, and steadily declined through the end of the trial. However, these decreases occurred independent of any differences in core temperature, perceived exertion, or heart rate. As the authors note, the observed impairment in exercise performance based on hotter ambient conditions is most likely not the result of increases in body temperature nearing an unsafe level, but an anticipatory adjustment in muscle recruitment to prevent thermoregulatory derangement in later stages of exercise. These results demonstrate the ongoing central regulation of muscle activity during exercise, based on peripheral feedback.

A second component of the CSM, well established in previous literature, is the notion that conscious anticipation or perception of exercise duration and intensity affects pacing strategies, performance, and perception of exercise intensity.[77,88-93] Given that fatigue and exercise intensity are only limited by peripheral mechanisms, an individual's perception of their duration or intensity of exercise should have no effect on performance.[75,81] However, this assumption has been shown to be false. Rejeski and Ribisl[94] demonstrated that perceived exertion differed based on the expectance of different durations for a bout of running. In the study, subjects were required to run for 20 minutes on a treadmill on two separate occasions, however for one session, subjects were told beforehand that they would be running for 30 minutes. Despite running intensity and physiological variables not showing any difference, ratings of perceived exertion were found to be lower at 20 minutes for the session where subjects were given incorrect information on exercise duration. This study suggests that the fatigue experienced by an individual cannot simply be determined by peripheral feedback on exercise intensity but is a more complex cognitive function related to an individual's perception of the impending duration of exercise.

In a study assessing this same effect during shorter bouts of exercise, Ansley et al.[77] mislead subjects by telling them they would be performing four maximal power output cycling trials lasting 30 seconds, and one trial each for 33 and 36 seconds. However, subjects actually performed two trials for each duration and the actual duration of each trial was not revealed to the subjects. The results showed significant reductions in power output across the final 6 seconds of the 36 second deception trial (where subjects believed they would be pedaling for 30 seconds), but not in the anticipated 36 second trial. Additionally, the fatigue index was equivalent at 30 seconds of exercise across all trials.

A final component of the CSM established in previous research is the concept of a "metabolic-reserve" at the end stages of self-regulated, fatiguing exercise.[82,83,87,93,95] This "metabolic-reserve" describes the ability of athletes to increase their recruitment of muscle and therefore intensity of exercise at the very end of a fatiguing bout of exercise, given that the duration or distance of exercise is known.[75,81] These findings are in direct opposition to the process proposed by linear models of fatigue. If fatigue occurs as a linear process of the accumulation of metabolites, muscular damage, oxygen deficit, and so-on, it would be impossible that the skeletal muscle recruitment and exercise intensity could be increased to its highest levels directly before termination.[75,81] Based on a linear model, this is the point where the accumulation of "fatigue" should be at its highest.[75,81] The only explanation for this is that central regulation of exercise intensity conserves energy based on subconscious or conscious pacing strategies and continuous feedback throughout sub-maximal exercise.[75,81]

While current research and thinking provides significant support for the CSM, it is not without criticisms or short-comings. The first broad short-coming is related to the notion that under the CSM model of fatigue, the determination of fatigue must be made as a self-reported measure.[75,96] Subsequently, other models of fatigue may be more applicable in studying mechanistic or peripheral components of total fatigue. For example, in studying the effects of local muscle fatigue the Neuromuscular or Muscular Trauma models may be more applicable, because under these models, local muscle fatigue can be quantified by declining muscular activation, strength, or changes in muscular contractile properties. However, under the taxonomy of fatigue described by Enoka and Duchateau[32], studies of this nature would fall under determining the contributors to *performance fatigability*, which in turn, informs the development of fatiguing sensations. Further, in keeping with a model of fatigue that incorporates the sum of thirty plus years of research, actual fatigue can only be measured by self-report, as it is determined by a culmination of peripheral factors. [32]

A second criticism, described by Marcora et al.[97], is the idea of a central governor, which subconsciously adjusts skeletal muscle recruitment in an effort to avoid drastic shifts from homeostasis. This idea is at odds with research showing that motivation can effect peformance and perceived exertion during exercise bouts. Instead a modification of this portion of the CSM is proposed that incorporates a more conscious control of force output in response to both perceived exertion and psychological or motivational factors.[97] Indeed, much of the previously discussed research has shown that perceptions of exercise intensity, which are made consciously, can influence the regulation of work output and pacing during fatiguing bouts of exercise.[77,88-93] Furthermore, as noted by Smits et al.[98], the idea of a subconscious central governor is not in line with ecological theories of movement control and does not incorporate the reciprocal relationship between perception of fatiguing sensations as a result of peripheral feedback and adjustments to work output to prevent total exhaustion.

In summary, the CSM of fatigue proposes a more interactive role of peripheral fatiguing mechanisms than previously proposed models focusing on a given discipline's view of fatigue.[15,72,73] Under the CSM, these peripheral systems function to provide continuous feedback to the central processing system during exercise on deviations from homeostatic conditions.[15,72,73] This feedback is combined with feedforward control related to conscious pacing strategies based on an individual's perception of peripheral feedback.[15,72,73] Based on these complex, interactive factors, the central processing centers in the brain then regulate skeletal muscle recruitment to avoid catastrophic deviations from homeostasis, eventually terminating exercise well before these deviations would occur.[15,72,73]

2.2.2 Exercise from Low to Fatiguing Intensities and Cognitive Performance

The purported effects of a bout of aerobic exercise on cognitive task performance have varied greatly. In a review by Tomporowski[99], it was concluded that, overall, submaximal aerobic exercise facilitates specific aspects of information processing or cognitive abilities. Throughout the review, however, the author discusses how this effect differs greatly based on both the type of exercise (i.e. prolonged vs short durations or moderate vs high intensities) performed and the type of cognitive ability (i.e. complex computations or perceptive tasks vs decisional tasks) that is assessed.[99] This section will focus on the demonstrated effects of exercise, across varying intensities, on decisional task performance, as this literature aligns with Specific Aim 1 of the current study.

A number of studies have been published confirming a positive effect of exercise on reaction times in response to decisional cognitive tasks. [23,24,27-29,100-104] Often attributed to physiological "arousal", this effect has been shown to have an inverse, quadratic relationship with exercise intensity, whereby reaction times are improved through light to moderate intensities of exercise, but then decline at higher intensities.[23,27] In a study by Chmura et al.[23], a multiple-choice reaction time task was used to measure decisional cognitive performance during an incremental bout of running exercise. Reaction times decreased (improved) in a linear fashion with increasing exercise intensity, up until an average of 70-80% of maximal intensity.[23] After this threshold, reaction times increased (worsened) with higher intensities.[23]

This interaction of exercise intensity and decisional reaction times has been termed the "inverted-U relationship" and has been replicated in a consensus of past literature.[23,27-31] Across studies, exercise produces a facilitating effect on choice reaction times, up to the point where exercise exceeds, what Chmura et al.[23] termed, the "psychomotor threshold". However, the main inconsistency in these results is in the specific intensity at which this threshold occurs. Arent et al.[27] demonstrated an inverted-U relationship where reaction times began to increase (worse performance) between 55-65% of maximal intensity. In contrast, Reilly and Smith[30] reported increasing reaction times at approximately 40% of maximal intensity. Generally, these differences have been attributed to differences in sample characteristics, with studies utilizing more aerobically fit participants reporting higher thresholds. Confirming this, Budde et al.[105] reported a significant interaction between prior physical activity level and decrements in cognitive performance after high-intensity exercise.

As mentioned previously, many authors originally attributed the inverted-U effect of exercise on reaction times to increases in central "arousal", or improvements in central processes.[10, 45] These authors pointed to results, such as those reported by Kubitz et al.[106], demonstrating exercise-induced increases in brain activity.[99,101] Further, early studies also demonstrated correlational increases and decreases in plasma adrenaline and noradrenaline levels above and below the psychomotor threshold.[28,31,107] However, as noted by McMorris et al.[107], the interpretation of these results is limited as peripheral levels of adrenaline and noradrenaline are not always indicative of central levels. Additionally, more recent work focusing on fractionated reaction times has, at the least, put this theory in doubt.

Fractionated reaction times refers to the separation of reaction times into premotor and motor components.[102] The premotor component is determined by the time interval between the onset of the response-inducing stimulus and activation of the muscle group that will produce a response, and is meant to represent the central processing stages of a psychomotor task response.[102] The motor component is determined by the time interval between activation of the response muscle group and the initiation of a response, representing the motor stages of a psychomotor response.[102] From a broader view, the analysis of premotor and motor contributions to reaction time is thought to delineate between the cognitive and motor-adjustment processing stages of Sanders information processing model.[102]

Perhaps the most comprehensive of these studies is one by Chang et al.[108], assessing fractionated reaction times, utilizing quadratic and linear analyses across eight exercise intensities (20-90% of maximal intensity). The authors report no significant quadratic or linear relationships between premotor time and increasing exercise intensity.[108] However motor time showed a negative, linear relationship with increasing exercise intensity.[108] The authors also reported a significant, quadratic relationship between exercise intensity and “movement time”, with a threshold similar to those reported for total reaction times.[108] Movement time was defined as the time interval from activation of the response muscle to completion of the response task.[108] Similar to motor time, this variable is separate from the cognitive processing stages of a psychomotor response.

As noted by the authors, these findings would seem to indicate that the mechanisms by which exercise improve reaction times on decisional cognitive tasks are mainly through improvements to the peripheral components of reaction time.[108] These findings have been replicated by a number of prior studies, however the study by Chang et al.[108] was the first to include a wide-range of exercise intensities and analyses for linear and quadratic relationships.[24,27,102] Adding to this evidence is a study by Ogoh et al.[109], assessing the effects of prolonged exercise on both reaction time and cerebral blood flow. The authors reported a positive effect across 50 minutes of exercise on reaction times and accuracy of responses, despite significant decreases in cerebral blood flow.[109] Further, when cerebral blood flow was manipulated to increase blood flow during exercise, reaction times and accuracy remained unchanged compared to normal conditions.[109] A limitation of this study is that these effects were only established for one intensity of exercise (moderate), however the results still provide compelling evidence to support the hypothesis that the cognitive processes of decisional tasks are unaffected by exercise.

In regards to the effects of exercise at fatiguing intensities, much of the early literature has focused on short, anaerobic bouts of exercise at very high intensities.[110-114] Overall, the results of these studies were equivocal, with some showing no effect of fatiguing exercise on cognitive performance and others showing relatively small deficits after exercise. [110-114] Across these early studies, a wide-variety of heterogenous cognitive tasks were used, assessing constructs such as visual perception, using a visual search task[110,111], to orientation performance utilizing a topographical mapping task[114].

Several more recent studies have assessed the effects of longer duration, more aerobic-dependent exercise that results in fatigue, on decisional cognitive tasks.[23,25,26,115,116] The previously discussed study by Chmura et al.[23] utilized an incremental exercise protocol with an average duration of approximately twenty-one minutes that terminated at volitional fatigue by each subject. The authors reported small, significant increases in reaction times and inaccurate responses after the fatiguing bout of exercise compared to resting values. [23] Even larger increases were noted between reaction times seen before the "psychomotor threshold", and even those seen at intensities above the threshold before the onset of fatigue, consistent with the proposed inverted-U relationship.[23]

In another study by Kamijo et al.[115], an incremental, fatiguing protocol was performed on a cycle ergometer, lasting an average of eighteen minutes. The authors reported no effect of fatiguing exercise compared to resting levels, with reaction times almost identical post-fatigue and at rest.[115] However, there were increases in reaction times compared to lower intensities of exercise, before and at the psychomotor threshold.[115] Further, several other studies assessing the effect of prolonged, exercise-induced fatigue on performance on decisional cognitive tasks have reported an adverse effect that is small in size, similar to that of Chmura et al.[23, 25,26,116] One explanation for the differing results reported by Kamijo et al.[115] is that participants may have increased or maintained their speed of responses (reaction time) coupled with a decrease in the accuracy of their decisions. The accuracy of responses was not reported by the authors, however this effect has been demonstrated in response to a fatiguing bout of aerobic exercise in several other studies.[116,117]

In summary, the consensus of previous research has reported positive effects of exercise-induced arousal on performance on decisional cognitive tasks. [23,24,27-29,100-104] These positive effects have been reported to follow an inverted-U pattern, where reaction times decrease (improve) through moderate to moderately-high intensities (60-80%) for active populations.[99,101] After this threshold, often termed the psychomotor threshold, cognitive performance declines steadily at higher intensities. [11, 57] Finally, while some evidence has pointed to equivocal performance after a fatiguing bout of aerobic exercise, the majority of studies have demonstrated adverse effect of fatigue compared to rest. [23,25,26,115] Further, all prior work have reported an adverse effect when performance is compared to optimal levels, around the psychomotor threshold. [23,25,26,115]

2.2.3 Exercise from Low to Fatiguing Intensities and Psychomotor Performance

One substantial shortcoming of previous literature assessing the effects of exercise and fatigue on cognitive performance is the lack of a cognitive task that incorporates a significant motor component. The majority of studies describe a task that requires a range of limited motor responses from lifting and moving the hand a very short distance (11-44 cm) to a simple finger-press.[20,99,101] The term "psychomotor" is often used in reference to these tasks, however as first noted by McMorris et al.[20], a true psychomotor task, relevant for active individuals, should require the coordination of a more significant motor response. Working with this definition, several studies have assessed the effects of exercise and fatiguing exercise on a psychomotor task.

McMorris et al. [20] describe a psychomotor task where subjects were presented with three target gates (left, center, right) and a stimulus directing them to sprint through a target gate as quickly as possible. After a fatiguing bout of cycling, mean reaction times to the presented stimulus and mean movement times to the target gate both increased significantly compared to resting values.[20] The authors also assessed the effects of moderate intensity exercise (70% of maximum power output), reporting significant decreases in mean reaction times and no change in mean movement times, similar to previous research.[20] However the effects of lower and higher intensity exercise (below a fatiguing level) were not assessed. [20]

Studies by Royal et al.[21] and Aune et al.[22] assessed the effects of progressive exercise intensity on accuracy during a sport-specific psychomotor task. Royal et al.[21] assessed shooting accuracy and motor strategies during shooting in highly-skilled water polo players and Aune et al.[22] assessed hitting accuracy and motor strategies during hitting in skilled and recreational tennis. Both studies reported no effect of fatiguing exercise on skill-specific accuracy, however both also reported significant changes in the motor strategies used for shooting and hitting.[21,22] The authors hypothesize that motor strategies were altered to preserve accuracy. [21,22] Seemingly confirming this hypothesis, Aune et al.[22] reported no change in motor strategies and a resulting decrease in hitting accuracy in the group of recreational tennis players compared to skilled players. A significant limitation of both studies is that both psychomotor tasks utilized were: highly skill-specific, repetitive in nature where the target did not move across multiple trials and sets of trials, and lacking a decisional component.[21,22] It is likely then, that fatigue did not limit accuracy on these tasks simply because of the ability of highly-skilled athletes to perform a familiar, repetitive motor task even when fatigued.[21,22] Further, because the quickness of the motor response was not assessed, due to experimental constraints, alterations to reaction time in an effort to preserve accuracy could not be captured.[21,22]

In relation to the study by McMorris[20], the studies by Royal[21] and Aune[22,118] present conflicting results. One explanation may be that fatiguing exercise improves the accuracy of responses on a psychomotor task but limits the quickness of response. However, the more likely explanation lies in the previously discussed differences in tasks and populations studied in these second two studies, and the limitations that these present in interpreting their results. Further, while the study by McMorris[20] utilized a task with multiple choices, the task did not require a judgement of any sort after the presentation of the stimulus.[20] Participants were directed to the correct option, and therefore the relationship between accuracy of judgements and speed of response to a motor stimulus could not be determined.[20] Subsequently, it is hard to draw any concrete conclusions on the effects of fatigue on psychomotor performance based on these three previous studies.

Finally, in a study only assessing sub-maximal exercise intensities, Mroczek et al.[119] used a task requiring participants to perform a vertical jump as quickly as possible in response to a random light stimulus. Reaction time was measured with an OptoJump system at rest and after 4 sets of a simulated volleyball game.[119] It was found that reaction times were significantly lower (-8.3% to -13.3%) after each set of volleyball compared to rest.[119] One limitation of this study is that exercise intensity was not explicitly measured, however blood lactate concentrations did not reach above 2.0 mmol after any of the sets of exercise, therefore it can be surmised that the intensity of exercise was light to moderate.[119] Another limitation, related to the psychomotor task used, is the lack of a decisional component. Participants were only asked to jump as quickly as possible after presentation of the stimulus, therefore the only relationship assessed was with simple reaction times.[119]

In summary, previous research on the effects of fatigue on psychomotor task performance has been limited to a small number of studies.[20-22] Additionally, the consensus of this research is hard to ascertain due to differences in the psychomotor tasks used and the variables obtained from these tasks. [20-22] Past research assessing the effects of sub-maximal exercise intensities is even more limited, with only two studies to the authors knowledge.[20,119] The results of both studies point towards an arousing effect of exercise at sub-maximal intensities, similar to the effects of exercise on cognitive performance discussed in the previous section.[20,119] However, like the effects of fatigue, both studies hold several limitations in the interpretation of these results related to the tasks used. Further, several components of this arousing effect have not been addressed by either study, namely the effect of continuous, increasing exercise intensities.[20,119]

2.2.4 Exercise from Low to Fatiguing Intensities and Performance on Affordance-based Measures

Limited and mixed results have been reported on the effects of fatigue and increasing exercise intensity on psychomotor performance, as discussed in the previous section. More importantly, significant limitations in the psychomotor measures utilized in these studies were identified. From an affordance-based perspective of movement control, outlined previously, these measures fail to capture the ability of an individual to accurately perceive their action capabilities and boundaries, and act accordingly based on their judgement.[3] In this way, previous research on psychomotor performance fails to capture the role that fatigue may have on perceptual-motor calibration and the need for re-calibration. Only one previous study has assessed the effects of fatigue and exercise intensity on perceptual-motor calibration, utilizing an affordance-based task.[13]

In this study, Pijpers et al.[13] assessed changes in judgements of maximum reaching height after several bouts of rocking climbing that were progressively longer, and therefore more strenuous/fatiguing in nature. The authors reported a significant effect of exercise "intensity" (determined increasing the duration of climbing bouts, not rate of work) on the accuracy of action boundary judgements. Judgements showing a significant, positive (increased accuracy) trend through the first three intensities, and then leveled off at the highest two and after the fatiguing bout. [13] These results would seem to demonstrate that the accuracy of judgements on an affordance-based task follow a similar, inverted-U trend from low to high intensities of exercise demonstrated in cognitive measures.[13] Alternatively, these results show the opposite for fatigue, with no decrements in judgement accuracy related to the bout of exercise that was performed until volitional fatigue.[13] However, several significant limitations in experimental design and observed results limit the ability to draw this conclusion with certainty.

First, the judgements of maximum reaching height were performed on the climbing wall, as the ability to judge the maximum reaching height of a given rock from a set position on the wall. [13] Given that rock climbing was the mode of exercise, it may be that judgement accuracy increased from rest, and with length of climbing bouts, simply because the participants were performing a form of exploration while exercising. Related to this, a systematic over-estimation of maximum reaching height was seen at rest (≈ 9 centimeters (cm)).[13] Further, the magnitude of change in actual maximum reaching height from rest to exhaustion was relatively small (≈ 4 cm), and changes from rest to lower intensities were even smaller.[13]

Therefore, it could be that participants were simply lowering their judgements of reachability based on perceived exertion (which increased significantly with each bout), rather than real changes in their action capabilities. More to the point, this also means that the design of either the fatiguing protocol or affordance task (or both) failed to induce a significant limitation to action capabilities or boundaries. Regardless of which, the need for perceptual-motor re-calibration was not induced, further limiting the interpretation of the results.

Another limitation is related to the interpretability of the selected exercise intensities, where intensity was set based on the length of climbing bouts instead of an objective measure, such as heart rate. While ratings of perceived exertion (RPE) did increase across each intensity of sub-maximal exercise (Borg RPE = 11.1 – 17.2), blood lactate concentrations did not.[13] Further, mean blood lactate concentrations only reached 3.3 mmol, which is not indicative of a high exertion level.[13] It is hard to determine, therefore, whether the participant's feelings of exertion were anchored to actual increases in fatigue, or simply the knowledge that the bouts of climbing were increasing in duration. Likewise, it is hard to compare the trend in accuracy of judgements with increasing exercise intensity to previous studies on cognitive performance without comparable definitions of each intensity level.

The study by Pijpers et al.[13] demonstrates some evidence for an effect of sub-maximal exercise on improving performance on an affordance-based task. Further, it provides compelling evidence that fatiguing exercise may have a differing effect on affordance-based measures, with no associated decrements in performance, compared to what is suggested from literature on cognitive and psychomotor performance. However, there is clearly a need for improvement in the experimental design used by Pijpers et al.[13], leading to the ability to draw more concrete conclusions in both of these areas.

2.3 INTERACTION OF LOAD CARRIAGE AND FATIGUE

2.3.1 Effects of Load Carriage on Physiological Stress During Physical Activity

Load carriage, in terms of those experienced by the majority of occupational athletes, describes the carrying of external loads secured to the body. These loads come in a number of forms, including back- and chest-worn packs, body armor or personal protective gear, breathing apparatuses, utility belts, and helmets. While the magnitude of the carried weight can also vary greatly, occupational athletes are often required to carry loads in excess of 45% of their body weight, which is anywhere from 23 to 38 kilograms (kg) for an average adult.[120,121] As one would expect, load carriage, especially of this magnitude, has a significant impact on the physiological stress associated with physical activity, and therefore the development of fatigue. This section will outline previous literature addressing the effects of load carriage on basic physiology and occupational athlete performance.

At the level of basic physiology, previous research has shown increases in normal physiological processes involved with moderate to long duration exercise at most intensities of exercise.[122-124] Borghols et al.[122] conducted a study where oxygen uptake, heart rate and ventilation were assessed while carrying loads of 0, 10, 20 and 30 kg. The effect of each weight was also assessed at three different intensities of activity, 29-39%, 50%, and 75% of maximum intensity.[122] The authors report a linear increase in all variables with increasing load carriage across all intensities, with the exception of oxygen uptake.[122] When at an intensity of 75% of max, a non-linear trend in oxygen uptake was observed with increasing load carriage.[122] However, all weighted conditions showed significantly greater oxygen uptake compared to the unloaded condition.[122]

The results of this study demonstrated an expected effect of load carriage, increasing oxygen uptake, ventilation and heart rate, in a mostly linear fashion, to meet the demands of a higher workload.[13, 41, 82] In another article by Polcyn et al.[124], with a higher sample size, the author's described the combined results of several studies assessing the effects of load carriage on oxygen consumption during treadmill walking. A range of weights from 12 to 50 kg was used across these studies.[124] The authors reported a significant linear trend, with approximately 40% of the variance in oxygen consumption explained by the amount of weight carried.[124] This is a large effect of load carriage, given the number of other factors that can effect oxygen consumption at a given intensity of exercise (i.e. aerobic capacity, muscle mass, body weight, height, leg length).

Building on this, a wealth of literature has identified significant decrements in performance on occupation-specific courses or tasks.[35] In a review by Carlton & Orr[35], twelve studies on the relationship between occupational performance and load carriage all showed a negative impact on some aspect of task performance. Across these studies, a wide-range of performance tasks and occupational athlete populations were utilized. Frykman et al.[125] describe the effects of two different loads on performance times for an obstacle course in female military police officers. The obstacle course consisted of low hurdles, zig-zag runs, low crawling, overhead horizontal pipe traversal, wall traversal and sprinting.[125] A mean 48% increase in time to completion was seen between 14 kg and 27 kg, loaded conditions.[125] In contrast, Knapik et al.[126] describe decrements in performance on a 20 kilometer (km) road march (as well as on an obstacle course) in male special forces personnel and Park et al.[33] describe decrements in firefighter specific drills in male firefighters.

Furthermore, a number of studies demonstrate a graded effect of increasing load carriage weight and subsequent decreases in performance. In the study by Knapik et al.[126], loads of 34, 48, and 61 kg were carried, correlating to approximately 38%, 54%, 69% of the mean bodyweight of participants. The authors reported significant increases in 20 km march time with each additional weight, in the order of 25-51% increases[126] Utilizing much lower loads, Harper et al.[127] assessed the effects of 18, 27, and 36 kg loads (normalized weights unknown) on 10 km march times in male and female medical officers. The authors reported a significant main effect of load on march time, with 4% decreases from 18 to 27 kg, 23% decreases from 18 to 36 kg, and 15% decreases from 27 to 36 kg.[127] Finally, across studies included in the review by Carlton, the loaded weights range from 5.5 to 61 kg.[35] Although it is hard to make comparisons across studies, because of the previously discussed differences in samples and performance tasks, consistent decrements are reported across this range of loaded weight.[35]

In summary, research assessing the effect of load on physiological stress during physical activity has demonstrated significant increases in basic physiological processes to meet the demands of increased stress.[13, 41, 82] Further, significant decrements have been shown in occupation- specific performance across a range of activites, populations, and magnitude of load.[35] These decrements have been demonstrated utilizing loads that are, often, much lower than those routinely carried by occupational athletes, and utilizing tasks that are much shorter in duration.[120,121] Subsequently, it is clear that load carriage is a significant contributor to fatigue during training and operational task performance for occupational athletes.

2.3.2 Load Carriage and Performance on Affordance-based Measures

Load carriage presents a limitation to an individual's action capabilities, following the model of perceptual-motor calibration and re-calibration presented in earlier sections. As such, in order to accurately perceive their action boundaries and select appropriate movement strategies, an individual carrying an external load must be re-calibrated to their new action capabilities. In contrast to fatigue, a number of studies have examined the effects of load carriage on performance on affordance-based measures.[8,9,14,39,64] However, these studies hold significant limitations related to the generalizability to an athletic population.

In two studies, Palmer et al.[8,9] investigated changes in reaction time, optical field of regard, postural affordances, and movement pattern coupling angles induced by several configurations of load carriage ranging from 2.2 – 37.5 kg (≈ 2.5% - 45.2% of mean body weight). These changes were assessed across a range of tasks, from marksmanship and threat identification drills to drop-landings.[75, 76] The authors reported significant losses in optical field of regard with increasing weight, related to increases in trunk and head flexion during drop-landings.[75, 76] A loss in visual field means that the amount of information available to an individual is limited, possibly limiting their ability to perceive affordances. Postural affordances and movement coupling angles were also effected by load carriage during all tasks, with joint trajectories altered and center of pressure variability reduced by increasing weight.[75, 76] Finally, reaction times increased with load carriage during marksmanship and threat identification drills, with increases in weight showing greater effects.[75, 76]

While the work of Palmer demonstrates significant alterations to perceptual information, reaction time, and movement strategies during relevant, operational activities, it does not specifically address the effect of load carriage on affordance judgements. Pepping and Li[64] were the first to assess the effects of load carriage on affordance judgements, using a maximum jump-reach task. Their results showed a significant decrease in action capabilities with the addition of load, but only in the order of a mean 5 cm decrease in action boundaries.[64] In response to this perturbation, participants were able to adequately re-calibrate and perception errors were equivocal between loaded and unloaded conditions.[64] The applicability of these results is very limited, however, given that the weight for the loaded condition was set at 10% of bodyweight, well below normal load carriage for occupational athletes.[64] In a separate study, Lessard et al.[39] showed similar results in judgements of affordance for maximum horizontal jumping. However, load carriage was set at an even lower weight, 5% of bodyweight, and secured at a very non-functional position, the ankles.[39]

A study by Petrucci et al.[14] utilized carried loads of a more relatable weight (18.4 kg or ≈20% of mean bodyweight), comprised of a normal firefighting outfit and gear. Participants were required to judge their action boundaries for a number of firefighter-relevant tasks: passing through a doorway and passing over/under a hurdle.[14] The authors reported significant errors in action boundary judgements, ranging from 4.2 to 15 cm.[14] While this study holds several improvements compared to those discussed previously, a significant limitation in the relatability of the results to occupational athletes is presented by the assessment of body-scaled affordances. [14] In this way, the weight utilized for load carriage is almost irrelevant, given that accuracy of judgements were predominantly dependent on the ability to judge spatial properties of the body and equipment.[14] The more pressing limitation, however, is the fact that action boundary judgements were not compared to a control (unloaded) condition.[14] While the magnitude of judgement errors is slightly larger than those reported in previous studies, without a control condition it cannot be determined whether judgement errors were a function of load carriage or the affordance-tasks themselves.[14]

To summarize, several studies have assessed the relationship between load carriage and performance on affordance-based measures. [58, 75, 76, 78, 83] While a basis for the disruption of affordance judgement has been identified, studies assessing this construct directly have returned mixed results with limited applicability to occupational athletes related to the affordance tasks (body-scaled vs action-scaled) and load carriage weights (5% to 20% of bodyweight) utilized in them.[58, 75, 76, 78, 83] These studies point towards the need for research addressing the effects of load carriage at operationally-relevant weights on action-scaled affordance judgement. It is this piece that will provide evidence as to whether load carriage presents a significant perturbation to the perceptual-motor system for occupational athletes, therefore requiring intervention in an effort to re-calibrate and improve their movement strategy selection and decision making, or in ecological terms, their agency.[128] Further, it will provide evidence as to whether load carriage can serve as a potential mode of perturbation in assessing the ability of a person to re-calibrate, and thereby reduce their risk of injury and improve performance.

2.3.3 Interaction of Load Carriage and Fatigue on Cognitive Performance

A point that was not discussed in the previous section is the lack of any previous research addressing the interaction between fatigue and load carriage in relation to perceptual-motor calibration and affordance judgements. As outlined in Section 2.3.1, load carriage enhances the effects of fatigue during activities regularly performed by occupational athletes. Further, beyond basic exercise training, almost all military, police, and firefighting training and operational duties are performed while wearing some form of external load. Subsequently, as fatigue and load carriage are rarely experienced independent of each other, the determination of the interaction of these variables in limiting movement control would seem to be highly relevant. This section will further this justification by presenting literature addressing the interaction of fatigue and load carriage on a decisional cognitive task.

Eddy et al.[100] conducted a study where participants with a military background were recquired to perform a simulated road march on a treadmill, using variable grades of incline, in a loaded and unloaded condition. The loaded condition consisted of normal tactical gear for a military population, weighing 40 kg (48.6% of mean bodyweight).[100] The march lasted 105 minutes and cognitive performance was tested every 20 minutes with a choice-reaction time, auditory measure that simulated enemy and friendly gunfire.[100] The task required participants to either respond to the sound of enemy gunfire by pressing a button on their firearm, or suppress their response to the sound of friendly gunfire by not pressing the button. A significant main effect of time (fatigue) was found for both reaction time and accuracy on the cognitive task, meaning that reaction time and accuracy worsened with increasing time in both conditions.[100] A significant interaction of time and load condition was also found for reaction time and accuracy on the cognitive task.[100] However, the differences between loaded conditions peaked at the 65 minute mark, and then performance between the conditions became similar through the end of the protocol.[100] This may be related to the fact that the marching protocol was not progressive in exercise intensity and was also not designed to induce volitional fatigue.[100] Therefore, the normal linear or quadratic trends in cognitive performance were not observed in either condition.[100]

This study presents evidence of an additive effect of load carriage on the progression of fatigue during extended exercise, in terms of decisional cognitive performance. While this points towards the possibility of a similar effect on perceptual-motor judgements, the connection is limited. Previous research has demonstrated an effect of fatiguing exercise on decisional cognitive performance, and further, that load carriage exacerbates the progression of fatigue during exercise. Subsequently, the results presented by Eddy et al.[100] essentially serve to solidify the natural conclusions of connecting these two areas of research. Based on the limited literature discussed in the previous section, load carriage can independently effect perceptual-motor performance and one wouldn't expect this same effect on the decisional cognitive task used by Eddy. Therefore, research is needed into the interactive effects of fatiguing exercise and load carriage on performance on affordance-based measures. Further, research is needed on the interaction of progressive exercise intensities and load carriage, given that this relationship has also not been established in any previous work, even related to cognitive performance.

2.4 RE-STATEMENT OF PURPOSE

To summarize, previously literature has demonstrated a wide range of deficits to action capabilities in response to fatigue and load carriage. Given that fatigue and load carriage are commonly experienced variables for occupational and competitive athletes, this literature suggests that they may be highly relevant modes of perturbation in the study of perceptual-motor calibration and recalibration for this population. While several studies have begun to examine this relationship, there are several broad shortcomings and limitations across this research, including: a) methodological flaws, b) the use of body-scaled affordance tasks or tasks that are not relevant for a large number of athletic sub-populations, and c) the use of lower magnitudes of load carriage than are relevant for most occupational athletes. Further, no previous research has addressed the interactive effects of fatigue and load carriage on perceptual-motor control, which is an especially important relationship given the effects of additional external loads on exacerbating physical fatigue. Finally, previous research on cognitive and psychomotor measures has provided some tangential evidence for an effect of increasing exercise intensity on perceptual-motor control. This literature suggests that alertness and arousal are improved through light to moderate intensities of exercise, and then decline through higher intensities and fatigue. However, no previous research has directly addressed the relationship between exercise intensity and a measure of perceptual-motor control.

Therefore, the purpose of the current study was to establish the interactive and independent effects of fatigue and load carriage on perceptual-motor calibration, as well as the effects of increasing exercise intensity, building up to fatigue. In addition, we sought to establish these effects using: a) an affordance-based measure that was action-scaled and transferrable to a wide range of athletic sub-populations, and b) a magnitude of load carriage that is relevant for occupational athletes.

3.0 METHODS

3.1 EXPERIMENTAL DESIGN

The current study was cross-sectional in nature, utilizing a cross-over design with every participant serving as their own control. Within-participant comparisons were made to assess changes in the dependent variables in response to two independent variables; fatigue and load carriage.

<u>Independent Variables:</u>

- Fatigue:

  An incremental treadmill protocol was used to induce fatigue. The incremental fatigue protocol (IFP) included several stages with increasing intensities determined by heart rate response: light= 40-50 % of heart rate reserve (HRR), moderate= 60-70% of HRR, high= 80-90% of HRR. In this way, it was possible to determine the effect of exercise intensity on the dependent variables. The final stage was performed to volitional fatigue, induced by increasing incline.

- Load Carriage:

  Load carriage was induced using an adjustable, weighted vest worn around the chest and shoulders. Participants carried 30% of their body weight (30% BW).

<u>Dependent Variables:</u>

- Heart Rate (HR)
- Rating of Perceived Exertion (RPE)
- Rating on the Profiles of Mood State Questionnaire (POMS)

- Action Capabilities Assessment Task (ACAT):
  - Maximum Jump Distance
  - Rate of Force Development (RFD)
  - Judgement accuracy
    - Percentage of accurate judgements (% AJ)
    - Percentage of successful jumps (% SJ)
  - Reaction time

3.2 PARTICIPANTS AND SAMPLE SIZE

A healthy, young, and active population was targeted for recruitment in the proposed study. In total, 23 participants were recruited (Age (yrs) = 25.26 ± 3.26, Body Mass (kg) = 72.80 ± 15.66, Height (cm) = 170.26 ± 11.15) and gender was counterbalanced (12 men, 11 women) across the sample. The median score on the Tegner Activity Level Scale[129] for the sample was a 6 (IQR = 5 – 7), which corresponds to an activity level of being recreationally active in sports like tennis badminton, handball, racquetball, down-hill skiing, or jogging at least five times a week. A young population, within a tight age range, was necessary, as the physiological responses to exercise and onset of fatigue change with increasing age. Criteria related to physical fitness was based on ACSM recommendations for cardiovascular exercise, but at a more strenuous level to ensure the sample could tolerate the IFP.[130] The following inclusion/exclusion criteria were used:

<u>Inclusion Criteria:</u>

- Males and females, aged 18-35 years
- Physically active and able to tolerate high intensity exercise, defined as:

- Participating in purposeful physical activity at least 4 days a week for 45 minutes a day, including aerobic exercise performed at a high intensity (i.e. circuit training, Crossfit, running or biking at a pace where you are not able to converse with someone easily, or sports such as basketball, hockey, soccer, rugby, or lacrosse)

- Able to walk and run on a treadmill from low to high intensities for one hour consecutively
- 20/20 corrected vision, and ability to wear contacts to correct vision if necessary

Exclusion Criteria:

- Any neurological or vestibular disorder that would affect balance
- Any condition that would contraindicate exercise at a high intensity, determined by administration of the Physical Activity Readiness Questionnaire (PAR-Q)

A sample size estimation was performed for a repeated-measures analysis of variance (ANOVA) to address the interactive effects of fatigue (rested and fatigued) and load carriage (loaded and unloaded) on reaction times on the ACAT. PASS 15.0.3 software (NCSS, LLC, Kaysville, UT) was used to perform sample size calculation a-priori, based on the work of McMorris et al.[20]. It was determined that 23 participants would be necessary to achieve 81% power with the following criteria: a) repeated-measures design having two within-subject factors and each participant being measured 5 times, b) effect size of .6, c) alpha level of .05.

3.3 INSTRUMENTATION

3.3.1 Treadmill

A motorized Woodway treadmill (Model: 4Front, Woodway USA Inc., Waukesha, WI) was used to perform the IFP.

3.3.2 Heart Rate Monitor

A Polar HR monitor (Polar USA, Lake Success, NY) was used to measure HR response during the IFP. The HR monitor was worn around the chest, underneath the shirt, and HR (beats per minute) was transmitted wirelessly to the treadmill display or Polar watch. Heart rate was monitored continuously throughout the protocol and used to set the intensity for stages of the IFP. Further, maximum heart rate was used to confirm fatigue at the end of the protocol.

3.3.3 Borg Scale

The Borg scale for RPE was used to assessed perceived exertion before, during, and at the termination of the IFP. The Borg scale uses a 6-20 scale to determine an individual's perception of their exertion level, with a 6 indicating "no exertion" and 20 indicating "maximal exertion. It was also used to confirm fatigue at the end of the IFP. It has been shown to be reliable and valid in measuring exertion when compared with objective measures of metabolic cost and exercise intensity.[131-133] Further, it has been used in a number of previous studies as a confirmation of fatigue.[19,21,104,134,135]

3.3.4 Eyewear

Senaptec Strobe Training Eyewear (SENAPTEC LLC, Beaverton, OR) contain curved, liquid crystal lenses that are able to block vision at intermittent periods set by the operator. These glasses were customized and connected to a controller to allow for manual blocking and clearing of the lenses. Further, the controller was integrated with the force plate software to allow for the syncing of force plate data with the timing of the lenses being cleared (visual information received) or blocked (visual information eliminated). The eyewear was used during performance of the ACAT to allow for calculation of reaction time on this measure.

3.3.5 Force Plate

Two Kistler piezoelectric force plates (Kistler, Amherst, NY) were used to collect ground reaction force data during the performance of the ACAT. A sampling frequency of 1000 Hz was used. Force plate data was collected with Vicon Nexus software (v. 2.6.1, Vicon Motion Systems, Oxford, UK), passed through an amplifier and analog to digital board, filtered by the software, and stored on a computer. Beyond characterizing the kinetics of the ACAT, the force plates were used, in concert with the Senaptec eyewear, to calculate reaction time. Finally, ground reaction force data was used to calculated RFD during jumping trials for the ACAT, and declines in RFD were used to characterize the state of fatigue at the end of the IFP.

3.3.6 Profiles of Mood-state Questionnaire

The POMS (short form) questionnaire was used to quantify change in fatigue state before and after the IFP.[136] Specifically, the "Fatigue" portion of the questionnaire was used. [136] This portion of the questionnaire consists of five items ("worn out", "fatigued", "exhausted", "weary", "bushed") that are rated by the individual on a 4-point scale from "Not At All (0)" to "Extremely (4)".[136] Scores are then summed to form a total fatigue score on a scale of 0-20.[136] This scale has shown excellent internal consistency (Chronbach's alpha = .90 - .94), and fair to good reliability (ICC = .43 - .66) consistent with expectations for mood states at rest.[137] Further, the POMS has been used to quantify fatigue across a diverse range of populations.[96,137,138]

3.3.7 Anthropometrics

A wall-mounted stadiometer was used to measure height and a standard, electronic scale (Life Measurement Instruments, Concord, CA) will be used to measure weight.

3.4 PROCEDURES

All participants reported to the NMRL for two testing sessions: one with load carriage (loaded), and the other without (unloaded). Session order was randomized using a simple randomization procedure (ABAB etc…). Approval for all testing procedures was obtained from the University of Pittsburgh Internal Review Board prior to any participant testing and written informed consent was obtained from all participants.

Participants were asked to wear clothes comfortable for exercise, including athletic footwear. During the first visit, all procedures were reviewed, written informed consent was obtained, and demographic and anthropometric measures taken. The remaining test procedures followed the outline detailed below.

The unloaded testing session consisted of performance of the IFP, with performance of the ACAT occurring before, during and after exercise. The loaded session was identical in nature to the unloaded, except for the presence of load carriage while performing the ACAT at all stages of testing. Ordered of sessions was randomized and counterbalanced across the sample. Participants were outfitted with an adjustable, weighted vest worn around the shoulders and chest. The vest was adjusted to 30% BW, representing a weight close to those reported to be carried by occupational athletes.[120,121] While 30% BW represents a more average load compared to some previous reports in occupational athletes, it was selected based on presenting a significant physical limitation, while still allowing for the safe performance of the ACAT.

Incremental Fatigue Protocol:

The IFP was selected based on a number of considerations. First, it was developed based on its ecological validity. A number of previous protocols in past research have utilized shorter bouts of more locally fatiguing exercises, such as repetitive jumps, short bouts of sprinting on a cycle ergometer, or repetitive contractions on an isokinetic dynamometer.[18,139-143] While these protocols may be more expedient, and effective in the study of peripheral factors related to performance fatigability, they hold little ecological validity in terms of the type of exercise-induced fatigue that is experienced by athletic populations.[96] For these populations, fatigue is generally not a result of acute bouts of high-intensity activity, but rather, an accumulation of activity at varying intensities.

Along these lines, several previous studies have also utilized more functional protocols, involving several bouts of functionally relevant movements (i.e. agility movements, jumping, shuttle runs), that are performed over long periods of time and involve oscillations in the intensity of activities.[19,134,135,144] These protocols would seem to hold the greatest ecological validity in replicating a natural progression of fatigue. However, these types of protocols are not conducive to setting specific ranges of exercise intensity, based on a quantitative measure like HRR. Therefore, from a pragmatic standpoint, they were not conducive to one of the primary aims of the study; determining the relationship between increasing exercise intensity and accuracy and reaction time on the ACAT.

In light of these considerations, several previously described protocols were reviewed that involved longer durations, specific and progressive intensities of exercise, and were meant to induce fatigue at the end of the protocol (summarized in Table 1).[21,23,116,145] The current protocol was developed most closely to that described by Collins et al.[145], shown to induce fatigue (mean decrease of 20 centimeters in vertical jump height) across a 55:00 minute bout of exercise. This protocol has also been used by Sanna and O'Connor[146] in another previous study. Slight alterations were made so that each sub-maximal stage included a set intensity, in consideration of the intended analyses discussed above, and so that the final stage was determined by volitional fatigue, so as to ensure total fatigue at the end of the protocol.

Table 1: Summary of incremental fatigue protocols used in past studies

Author (Year)	Description	Average Duration (min)	Measure(s) of Fatigue
Chmura et al. (2010)	Treadmill running; speed (6 km/h start) increased every 3 minutes until volitional fatigue	36:00	Blood Lactate = 9.84 mmol/L; HR = 98% of age-predicted max
Collins et al. (2016); Sanna & O'Connor (2008)	Three, 15-min stages of running/jogging alternating intensities of 35, 55 and 95% of max; one final bout of 10-min, alternating 55 and 95% of intensity	55:00	Decrease in Vertical Jump Height = 20 cm; RPE (Omni Scale) > 6.8
Royal et al. (2007)	Four sets of polo-specific drills with decreasing time to complete across each set	31:00	RPE = 19.1; Blood Lactate = 7.27; HR = 89% of age-predicted max
Thomson et al. (2009)	Treadmill running; speed (9km/h) increased by 1.8 km/h every 3 minutes until volitional fatigue	27:00	VO_2 Plateau or RER >1.15

In light of these considerations, and based on established protocols, the resulting IFP was performed on a treadmill. Resting measurements for RPE, HR, and POMS were collected prior to exercise, and familiarization trials for the ACAT were performed. Participants were then given a 10-minute warm-up at 3.5 mph and 0% incline, either loaded or unloaded, to allow for the warm-up to be specific to the condition that they would perform the ACAT in for the remainder of the session. This was the only portion of the session for which the participant was loaded while on the treadmill. Following the warm-up, baseline trials of the ACAT were performed, and then the IFP proceeded in 4 stages:

- Light Intensity: 15 minutes, 40-50% of HRR
- Moderate Intensity: 15 minutes, 60-70% of HRR
- High Intensity: 15 minutes, 80-90% of HRR

- Fatiguing Stage

For the first three stages with set exercise intensities, treadmill speed was adjusted to obtain the necessary zone for HRR. Heart rate reserve was determined by subtracting the participant's resting HR from their age-predicted maximum HR (220-age). For the fatiguing stage, participants started at the final speed used for the high intensity stage and treadmill incline was increased 1% every minute until volitional fatigue.

Heart rate was monitored continuously throughout the protocol and recorded every five minutes. Ratings of perceived exertion were collected in the last minute of every stage. Ratings of fatigue using the POMS were obtained again after termination of the fatiguing stage. Finally, the ACAT was performed again at the end of every stage. An outline of the IFP and timing of measures is provided in Figure 2.

ACAT:

The ACAT was developed based on action-scaled, jumping tasks described in previous literature, with minor modifications to allow for the collection of ground reaction forces (GRF) and reaction time during trials.[48,49] Participants began by performing several maximal broad jumps to obtain a measure of the action boundary for the task. For maximal jumps, participants began on the force plates in a parallel stance, and feet approximately shoulder-width apart. Participants were instructed to jump as far as possible while still successfully landing on both feet. Three sub-maximal warm-up trials were given, and participants then performed three maximal jumps with one-minutes rest between. The farthest of the three was recorded and used as their action boundary. For all other stages (warm-up through post-fatigue) the action boundary was measured again by having participants perform two maximal jumps at the beginning of each set of measurements.

Participants were then outfitted with the Senaptec eyewear and familiarized with the ACAT. Participants began on the force plate, with their vision blocked. While their vision was blocked, a marker was placed at a percentage of their action boundary: 95, 100, or 110%. After the marker was placed, participants were instructed to 'get ready' and after a period of 1-2 seconds, the control for the Senaptec eyewear was switched, clearing their vision. The participants assessed the jump distance presented by the marker and either indicated that they could jump it by performing the action or indicated that they could not by jumping to the side. A successful jump was considered one where the participant landed with both heels completely on the opposite side of the marker. Participants were instructed to assess the jump distance as quickly as possible, while still making accurate judgements. After each trial, participants were given a short rest while the marker was reset. Order of jump distances was block-randomized so that each distance appeared the same number of times but in a completely random order. Order was randomized for the first session for each participant, and then the same order was replicated for the second session. In the case of a given distance appearing twice in a row, the marker was still reset so that no indication was given that it was left in the same spot. The experimental set-up and examples of the two response actions are depicted in Figure 3. A colorless mat was used for the jump surface, all markings that could be used as a reference for distance were removed from the floor, and no feedback on judgement accuracy was provided.

A reliability study was performed for these procedures, finding that 6 familiarization trials at the beginning of a session were necessary to limit any between- or within-session systematic bias. Further, 6 testing trials were sufficient to obtain excellent reliability (ICC = 0.930) and to maximize within-subject stability (Coefficient of Variation = 9.50%). To ensure that participants were completely familiarized with the task, 12 trials of the ACAT were performed at the beginning of each session for familiarization, and then 6 were performed at every subsequent stage of testing (baseline through fatigue). Trials were collected as quickly as possible after each exercise stage to minimize the possibility of the effects of exercise wearing off. Jumping trials were initiated immediately after exercise was terminated for each stage (< 30 sec), and the mean time to complete all jump trials at the end of each exercise stage was under five minutes (Mean Testing Time (sec) = 280 ± 24).

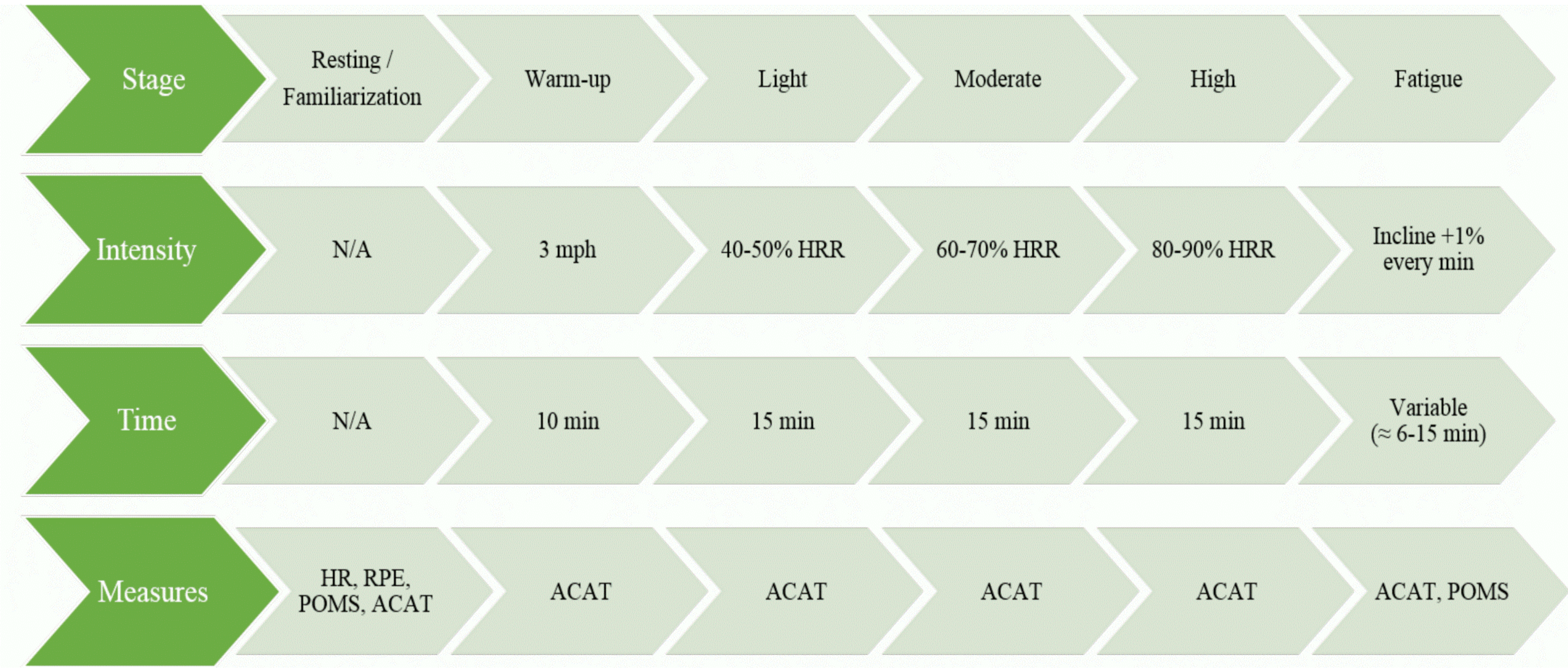

Figure 2: Schematic of incremental fatiguing protocol and timing of measurements

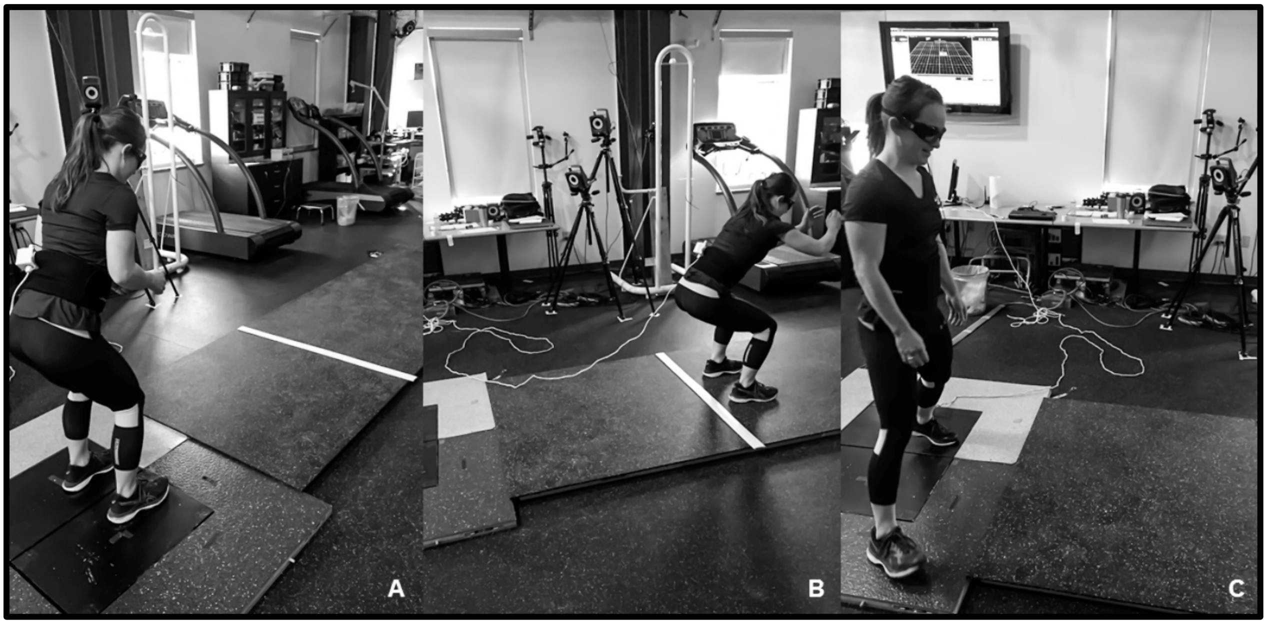

Figure 3: Experimental set-up for ACAT and example of response types

- A: Starting position, B: Jumping to indicate the marker is within reach, C: Stepping off to indicate the marker is not within reach

3.5 DATA REDUCTION

Judgement accuracy for the ACAT was calculated in two forms, firstly as the percentage of trials where an accurate judgement was made. An accurate judgement was considered any trial where either: a) jumping was afforded and the participant decided to jump, b) jumping was not afforded and the participant decided not to jump. An inaccurate decision was considered any trial where either: c) jumping was afforded and the participant decided not to jump, d) jumping was not afforded and the participant decided to jump. The percentage of accurate judgements for each assessment of the ACAT was calculated as: $\% \, AJ = [(a + b)/(a + b + c + d)] * 100$. The second form of judgement accuracy was calculated as the percentage of trials where the participant successfully completed a jump out of the total trials where a successful jump was possible. A successful jump was considered any trial where: a) the participant jumped and landed with both heels on the opposite side of the marker. A trial where a successful jump was possible was considered any trial where: b) the participant chose to jump and jumping was afforded. The percentage of successful jumps was calculated as: $\% \, SJ = (a / b) * 100$.

Both RFD and reaction time (RT) were calculated using a custom written Python script (Python Software Foundation, Guido van Rossum). Reaction time for each trial was calculated as the time interval between when participants received visual information (clearing of eyewear) and the initiation of movement, with a mechanical delay of 40 ms for the glasses to clear once switched factored in. Initiation of movement was determined by a decrease in vertical GRF above 10% of BW. A threshold of 10% was selected based on it being high enough to fall outside the normal variability of baseline ground reaction forces, and therefore eliminating false-positives. All of the variables (% AJ, % SJ, and RT) were calculated as averages across all valid trials. Trials were excluded where participants were observed to have moved prior to the glasses being cleared or where calculated RTs were found to fall outside of two standard deviations of the participant's mean RT.

Finally, RFD was calculated from ground reaction forces for maximal jump trials across each stage. RFD for each trial was calculated as the average change in vertical GRF across the concentric phase of the jump (N/s). The onset of the concentric phase was defined as the point of minimum GRF, indicating the transition from the eccentric to concentric phase of the jump. The end of the concentric phase was defined as the point of maximal GRF, indicating the subject's feet partially leaving the force plates. As two maximal jumping trials were collected at each stage, beyond the familiarization trials, the peak value across two trials was used for analysis. These methods were based on considerations outlined by Maffiuletti[147], and were shown to have good inter-session reliability (ICC = 0.671) in the previously mentioned reliability study (Section 3.4) conducted on the ACAT.

3.6 STATISTICAL ANALYSES

IBM SPSS Statistics 23 (IBM, Armonk, New York) was used for all statistical analyses. Descriptive statistics were calculated for all dependent variables across time points. Normality of all dependent variables were checked by use of Shapiro-Wilk tests and visual inspection of histograms. Mauchly's test was used to assess sphericity. The presence of outliers was assessed by use of stem and leaf plots. Alpha level for statistical significance was set a priori at $\alpha = 0.05$.

For data used to describe the effects of IFP (i.e. HR, RPE, POMS, Time, and decrements in maximal jump distance and RFD), statistical tests for mean differences between the loaded and unloaded sessions were performed, and variables were averaged across conditions when appropriate. For HR and RPE, a 2 x 5 repeated measures ANOVA was used to test for mean differences across stages of the IFP (rest through fatiguing stage) and by condition. For the remaining variables, paired t-tests were used to test for mean differences, with non-parametric tests used for non-normally distributed variables. In the case of maximum jump distance, where values would be expected to be systematically lower in the loaded compared to unloaded condition, a Wilcoxon Signed-Rank test was used to test for mean differences in the change in jump distance (peak to post-fatigue) between loaded and unloaded conditions.

3.6.1 Quantification of Fatigue

The quantification, or confirmation, of fatigue at the end of a fatiguing protocol varies greatly across previous literature. Several studies simply confirm fatigue in terms of volitional termination of the protocol, or even simply completing the defined demands of the protocol.[23,116,143,144] Some studies use objective measures, with commonly used measures including: decreases in maximal jump height or distance[19,135,141,145], decreases in force output during multiple isokinetic contractions[140,148], and physiological thresholds, such as percentages of max heart rate or lactate[20,23,149]. However, many of these measures, such as decreasing force output, may be more related to identifying peripheral factors that are a result of fatigue.[96] Further, as noted by Enoka[96], subjective ratings of exertion or fatigue capture an individual's perception of these culminating peripheral fatiguing factors, and are therefore considered a more valid assessment of total fatigue.

Subsequently, a combination of subjective and objective measures of fatigue were analyzed for the current study. This approach has been used across several studies in previous literature, in an attempt to provide the best evidence for the progression and culmination of fatigue.[19,20,135,149] Descriptive statistics for RPE were calculated to confirm exercise intensities across stages, as well as fatigue at the end of the protocol, with an RPE of 18 or higher indicating fatigue. [19,21,104,134,135] Descriptive statistics were also calculated for post-fatigue POMS values and changes in score on the POMS fatigue scale from pre- to post-fatigue measurements.

Decrements in anaerobic performance were tested for using paired t-tests to assess mean differences in both maximal jump distance and RFD from peak performance to post-fatigue measurements. Peak performance measurements were determined by the peak jump distance or RFD from trials following the moderate or high intensity stages of the IFP, as it was found that the majority of participants peaked in their maximal jumping performance in one of these two stages. To assess the degree to which participants recovered, if at all, across the post-fatigue ACAT trials, RFD was also calculated for the average of the 6, post-fatigue action boundary judgement trials, as well as the final 3 trials. For these averages, only trials where participants decided to jump were used. Paired t-tests were used to compare mean differences in RFD for the average of 6 and 3 action boundary judgement trials post-fatigue to both the post-fatigue and peak averages for RFD from the maximal jump trials. In the case of non-normal data, Wilcoxon Signed-Rank tests were used.

Finally, maximum heart rate was recorded from the final stage of the IFP and percentage of each participant's age-predicted maximum heart rate (%APM) that was obtained was calculated. Descriptive statistics are presented for both variables and compared to previously reported maximal heart rate values for fatiguing exercise.[19,149]

3.6.2 Main Analyses

To assess the main and interactive effects of increasing exercise intensity through fatigue (baseline measurement through post-fatigue) and load carriage (loaded and unloaded) on RT, a 2x5 repeated measures ANOVA was used. The interaction term was analyzed first. Given that the interaction term was significant, a one-way repeated measures ANOVA was used to test for the simple main effect of fatigue at each level of load carriage. If the interaction effect was not found to be significant, 2-way repeated measures ANOVA were used to test for the main effects of both fatigue and load, and pairwise t-tests, using Bonferroni corrected p-values, were used to perform marginal comparisons in the case of either main effect showing significance. Both the linear and quadratic terms were considered, given the expected nature of the effect of increasing exercise intensity on variables outlined in the hypotheses. In the case of non-normal data, Friedman's test was used in place of an ANOVA. Greenhouse-Geiser corrected p-values were used in the case of sphericity being violated. Finally, residuals were calculated and Cook's Distance values were examined to identify potential outliers having a high influence on the results of the ANOVA.

For %AJ, the distribution of scores showed significant departures from normality (SW Statistic = 0.605 – 0.798, $p < 0.001$). Therefore, to analyze the interactive effect of exercise intensity and load carriage, delta scores were calculated for differences in mean ACC between loaded and unloaded sessions across, and Friedman's test was used to test for mean differences across exercise intensities. Participants were then dichotomized into "poor" and "good" performers, using a cut-off of 83.33%. Cochran's Q tests were used to test for the main effect of exercise intensity, and McNemar's test was used to test for the main effect of load carriage, on ACC. The range of scores for %SJ was very limited (most participants scoring 100% for at least 1 session) and non-normally distributed (SW Statistic = 0.308 – 0.425, $p < 0.001$), therefore data were only analyzed qualitatively.

3.6.3 Exploratory Analyses

After examination of the initial results, several post-hoc analyses were performed. The first analyses were performed to examine the relationship between %AJ and RT, as participants progressed through the IFP. For this aim, RTs were averaged across load conditions for each measurement timepoint. Then, 2x5 mixed ANOVAs were run with exercise intensity as the within-subjects factor and the dichotomous grouping ("good"/"poor" performers) for %AJ, described earlier, as the between-subjects factor. Separate ANOVAs were run for both %AJ at baseline and post-fatigue. The interaction term was examined first, and post-hoc testing was completed as described above for the previous ANOVA tests.

A second grouping of post-hoc analyses aimed to establish whether more athletic individuals, determined by peak values for maximum jump distance and RFD, were more successful at maintaining RTs across fatiguing intensities or demonstrated better %AJ. To analyze this aim, separate repeated measures ANCOVAs were performed with exercise intensity as the within-subjects factor and either maximum jump distance or RFD as a covariate. The interaction term was examined first to ensure that no interaction existed between the covariate and dependent variables. Next, the main effects were examined to determine the effects of exercise intensity adjusted for either maximum jump distance or RFD. Post-hoc testing was then performed as described previously for other ANOVA tests. Given that %AJ was not found to be affected by exercise intensity, Mann-Whitney U tests were used to compare differences in maximum jump distance and RFD between individuals categorized as “good” or “poor” performers for %AJ at baseline.

Finally, a third exploratory aim was to establish whether the observed changes in RT over exercise intensities were related to the extent to which an individual’s action boundary was affected by the IFP. To test for this, a repeated measures ANCOVA was performed with exercise intensity as the within-subjects factor, and the maximum jump distance decrement (peak to post-fatigue) as a covariate. The ANCOVA was carried out as described above.

4.0 RESULTS

4.1 INCREMENTAL FATIGUE PROTOCOL

Descriptive statistics for HR and RPE across the IFP are presented in Figure 4. Mean HR and RPE increased through sub-maximal intensities, with maximal values during the fatigue stage indicative of maximal exertion (Mean HR (bpm) = 192 ± 6.2, Mean RPE (6-20) = 19.54 ± 0.85). Both variables were averaged across condition, as the results of the 2 x 5 repeated measures ANOVA found no significant effect of condition on HR ($F = 3.91$, $p = 0.061$, $\eta_p^2 = 0.151$) or RPE ($F = 0.04$, $p = 0.854$, $\eta_p^2 = 0.002$). For HR, there was a significant interaction of time (exercise stage) and load condition ($F = 3.907$, $p < 0.001$, $\eta_p^2 = 0.120$), however only the high intensity stage showed a significant difference ($t = -2.617$, $p = 0.016$) between loaded and unloaded conditions, and the difference was minimal (Mean Difference (bpm) = -3.45 ± 1.32). All participants were able to complete the protocol, and no adverse events were reported. The mean time that subjects completed on the fatiguing stage of the IFP also did not differ significantly between conditions ($t = -0.185$, $p = 0.855$), and the average time was 573 ± 125 seconds. Therefore, the mean total exercise time was 64.6 ± 2.1 minutes, including the warm-up.

Tests for mean differences revealed no significant differences between conditions in the change in POMS score ($p = 0.878$), maximum POMS scores ($p = 0.954$), maximum HR as a %APM ($p = 0.241$), change in maximum jump distance ($p = 0.211$), or RFD ($p = 0.068 - 0.083$). All variables were averaged across conditions. Mean changes (from pre/peak- to post-measurements) or simple means for all variables used to quantify fatigue induced by the IFP are summarized in Table 2, with the results of associated tests of mean differences (pre/peak- to post-measurements) where appropriate.

Finally, results for the tests of mean differences in RFD to assess whether participants recovered across post-fatigue action boundary judgement trials indicated that participants did not show significant recovery in RFD. Wilcoxon signed-rank tests indicated that RFD was significantly lower during action boundary judgement trials, using the average of 6 (2,809 N/s) and 3 trials (2,871 N/s), in comparison to mean peak RFD (3,661 N/s); $p \leq 0.001$. Further, Wilcoxon signed-rank tests indicated that RFD did not recover across the post-fatigue action boundary judgement trials in comparison to mean RFD for post-fatigue maximum jump distance trials (2,859 N/s), with no significant differences detected; $p = 0.761 – 0.976$.

Table 2: Descriptive statistics and results of tests for mean differences for variables used to quantify fatigue

	Mean Change (SD)	Mean (SD)	95% CI	p	ES
Max HR (bpm)		192 (6.44)	189.21 – 194.79		
Max HR (%APM)		98.62 (3.81)	96.97 – 100.27		
Max RPE (6-20)		19.54 (0.85)	19.18 – 19.91		
POMS (0-20)	16.22 (2.47)	17.78 (2.04)	15.15 – 17.28		
Max Jump Distance (cm)	-7.96 (7.17)		4.86 – 11.06	< 0.01	0.26
RFD (N/s)	-802.10 (716.24)		492.30 – 1,111.80	< 0.01	0.51

Table 2 (continued)

- SD = standard deviation, 95% CI = 95% confidence interval, p = result of Wilcoxon-signed rank tests, HR = heart rate, %APM = percentage of age-predicted max heart rate, RPE = rating of perceived exertion, N/sec = newtons per second, ES = Effect size (Cohen's D)

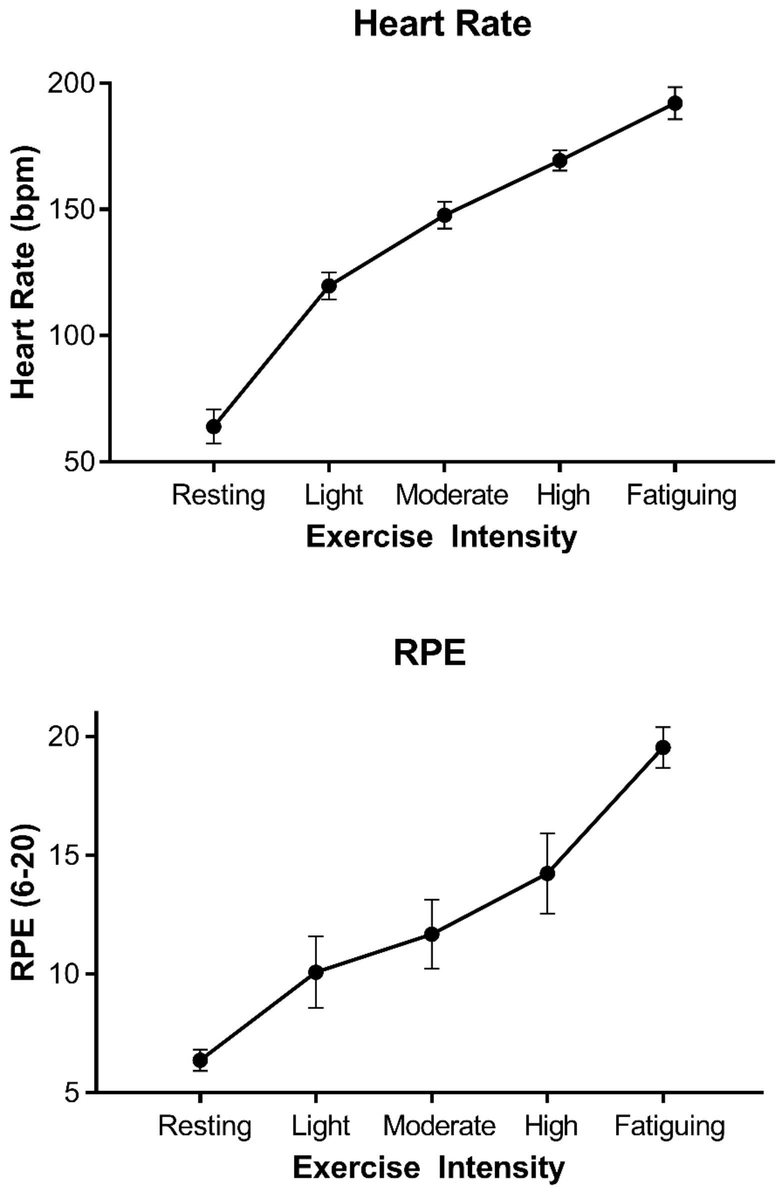

Figure 4: Mean heart rate and rating of perceived exertion by exercise intensity

- bpm = beats per minute, RPE = rating of perceived exertion on Borg Scale
- Values for fatiguing intensity indicate maximum values obtained during the stage; all other stages are reported as means
- Error bars indicate ± 1 standard deviation

4.2 REACTION TIME

Descriptive statistics for reaction time across stages of the IFP and by load carriage condition are presented in Table 3 and depicted in Figure 5. The results of the 2x5 repeated measures ANOVA showed no significant interaction effect of exercise intensity and load carriage (F (GG) = 0.390, $p = 0.815$), even when the quadratic term was considered ($F = 0.011$, $p = 0.916$). However, a main effect of exercise intensity was found to be significant, and quadratic in nature ($F = 18.587$, $p < 0.001$, $\eta_p^2 = 0.458$). Pairwise comparisons revealed a significant decrease in mean RT between baseline and the moderate intensity stage (Mean Difference (ms) = -38.25 ± 11.90, $p = 0.040$), and a significant increase in mean RT between moderate and fatiguing intensity stages (Mean Difference (ms) = +38.817 ± 11.33, $p = 0.024$). The main effect of exercise intensity is depicted in Figure 6, showing the quadratic, inverse pattern of RTs across increasing exercise intensity, peaking at a moderate intensity and increasing again through fatigue.

Examination of residuals and Cook's Distance values (Appendix A) revealed one observation with undue influence on the model, falling 3.3 standard deviations above the mean Cook's Distance value. A sensitivity analysis was performed by removing the observation, however no changes were noted in the results of the ANOVA and so the observation was retained in the model.

Table 3: Descriptive statistics for reaction time across stages of the fatigue protocol and by load carriage condition

	Baseline	Light	Moderate	High	Fatigue	Total
Loaded	486 (161)	451 (161)	453 (150)	460 (155)	484 (170)	466 (31)
Unloaded	467 (134)	436 (167)	423 (151)	459 (162)	470 (144)	451 (30)
Total	476 (26)	443 (30)	438 (27)	459 (29)	477 (31)	459 (31)

- All values presented in milliseconds and as mean (standard deviation)

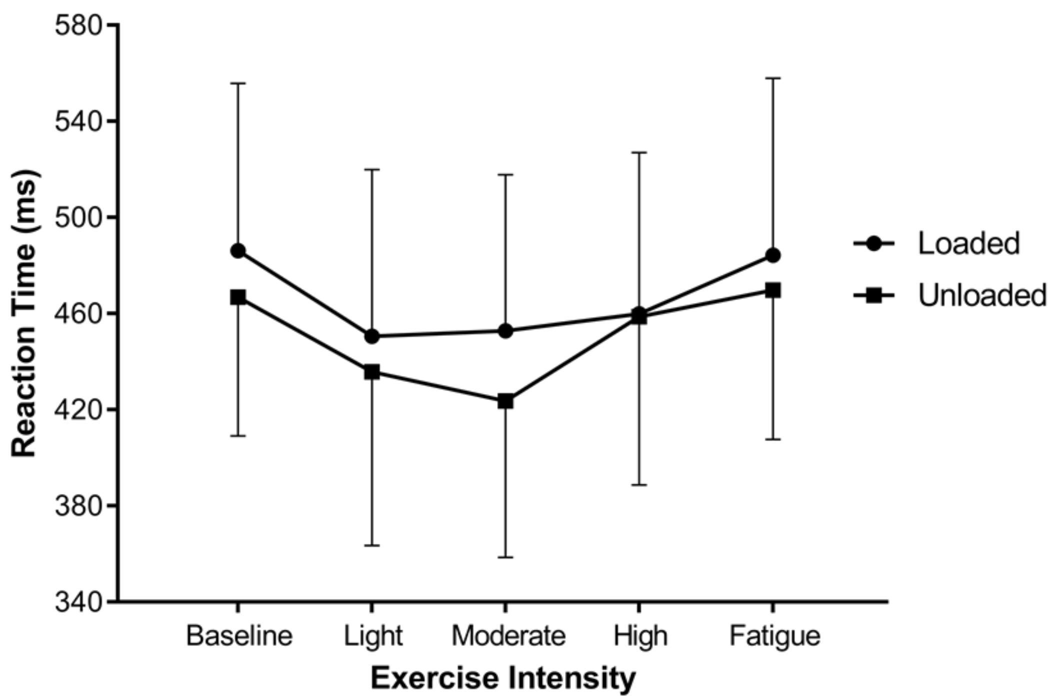

Figure 5: Mean reaction time by exercise intensity and load carriage conditions

- ms = milliseconds
- Error bars indicate 95% confidence interval upper (loaded) and lower (unloaded) bounds

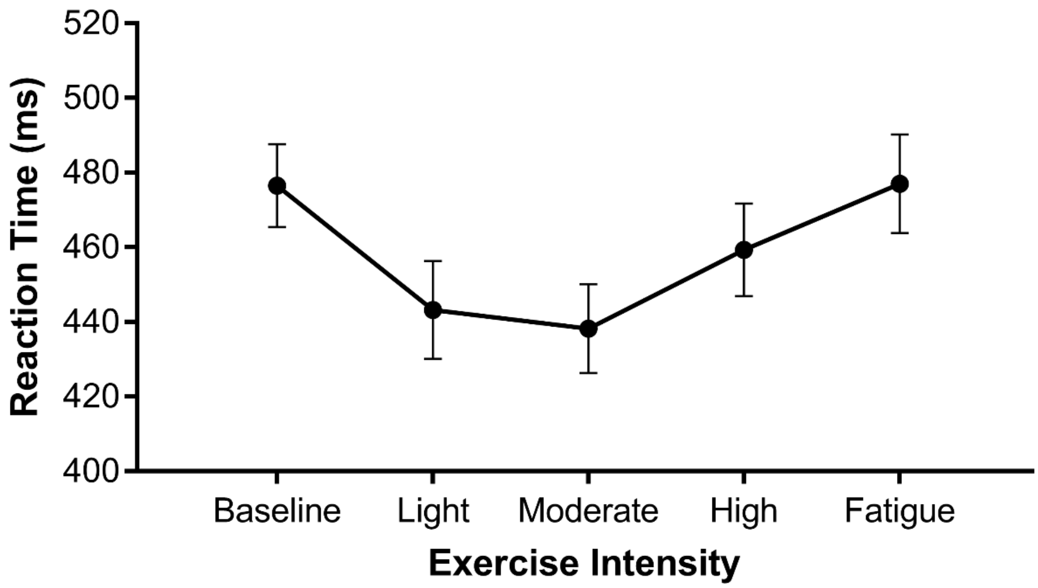

Figure 6: Mean reaction time averaged across load carriage conditions by exercise intensity

- ms = milliseconds
- Error bars indicate 95% confidence intervals

4.3 JUDGEMENT ACCURACY

Descriptive statistics for %AJ by exercise intensity and load carriage condition are presented in Table 5 and depicted in Figure 7. On visual inspection of Figure 7, it appeared that mean %AJ was slightly higher in the unloaded condition across all stages of the IFP, however it did not appear to show any pattern with increasing exercise intensity. A 2x5 ANOVA was the planned analysis for the effects of exercise intensity and load carriage on %AJ, however the results showed a non-normal distribution for %AJ. Therefore, non-parametric tests were conducted.

To test for the interaction of exercise intensity and load, delta scores were first calculated for each participant for the difference in %AJ between loaded and unloaded conditions at each exercise intensity. Friedman's test was then used to test for differences in delta scores across exercise intensities, revealing no significant differences ($p = 0.79$). Based on the frequencies of scores, participants were then dichotomized into "poor" and "good" categories, based on either scoring below or above 83.33% respectively (Figure 8). Cochran's Q test was then used to test for differences in the proportion of participants scoring in the good category across exercise intensities. For both the loaded (Cochran's Q = 5.78, $p = 0.33$) and unloaded (Cochran's Q = 0.59, $p = 0.99$), no significant effect of exercise intensity was detected. Finally, McNemar's test was used to test for the effect of load, comparing differences in the proportion of participants scoring in the good category at baseline. No significant effect of load was found ($p = 0.51$).

Table 4: Descriptive statistics for judgement accuracy across stages of the fatigue protocol and by load carriage condition

	Baseline	Light	Moderate	High	Fatigue	Total
Loaded	88.6 (13.0)	91.7 (10.0)	92.4 (12.3)	90.2 (14.2)	86.4 (12.2)	89.9 (12.3)
Unloaded	91.7 (13.4)	93.9 (9.7)	93.9 (9.6)	93.2 (11.1)	93.9 (8.2)	93.3 (10.4)
Total	90.2 (13.2)	92.8 (9.85)	93.2 (11.0)	91.7 (12.7)	90.2 (10.2)	91.6 (11.4)

- All values presented as a percentage and as mean (standard deviation)

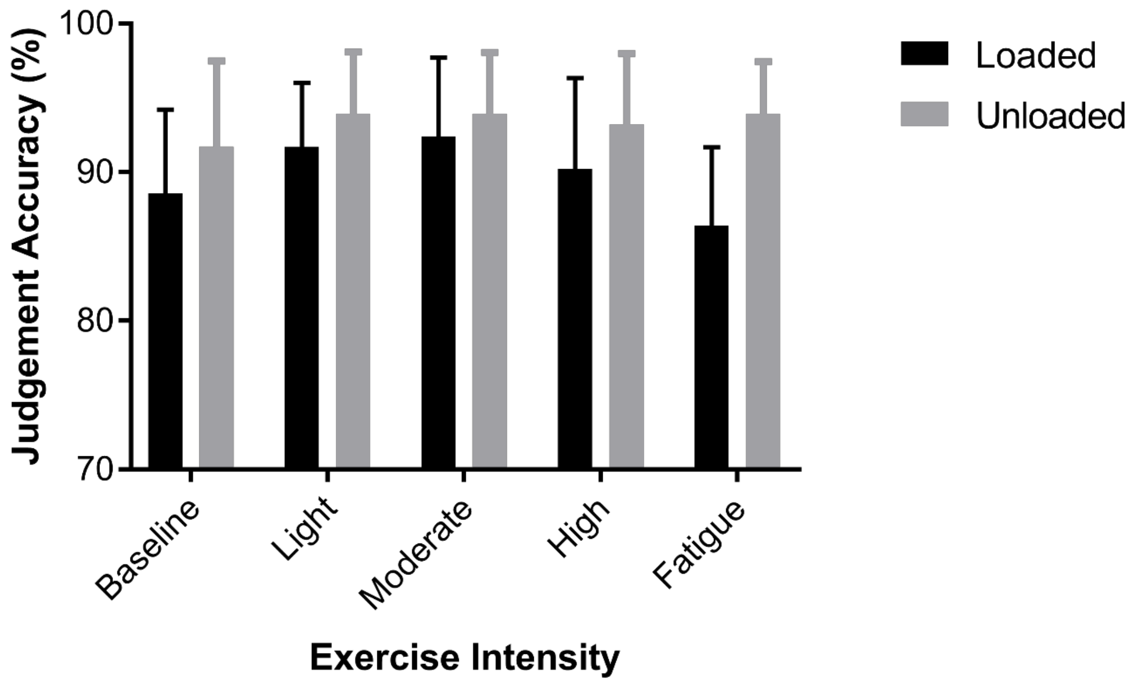

Figure 7: Mean judgement accuracy by exercise intensity and load carriage condition

- Error bars indicate 95% confidence intervals

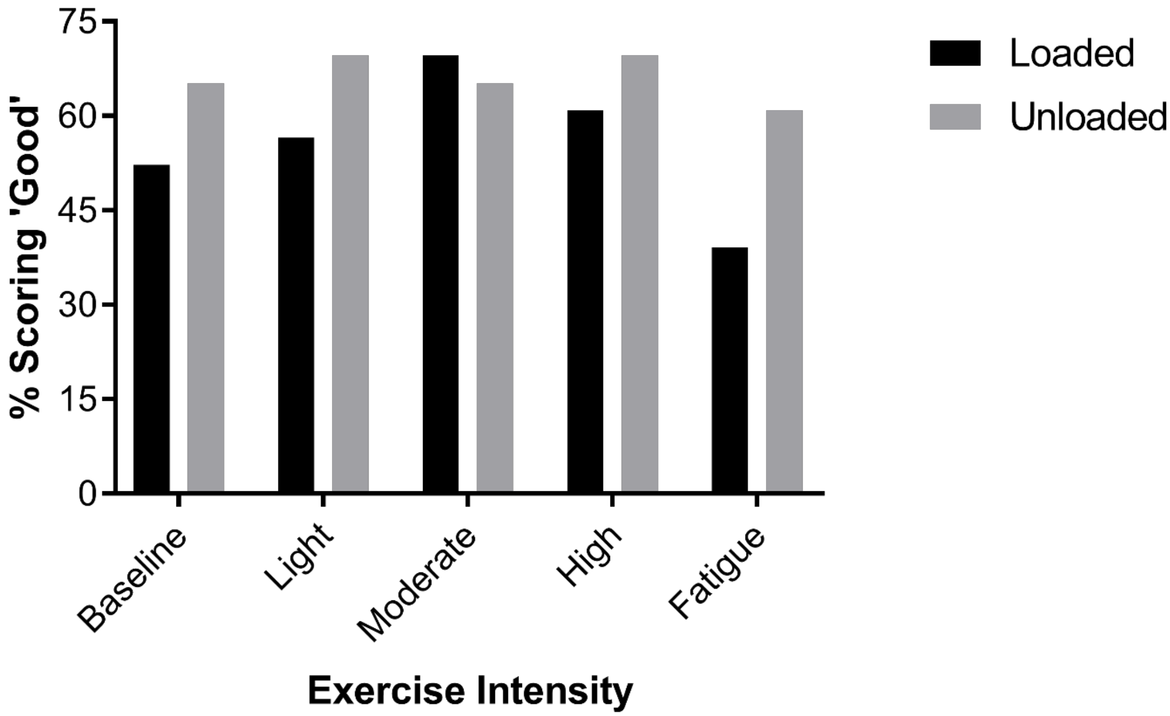

Figure 8: Participants scoring "good" for judgement accuracy by exercise intensity

4.4 SUCCESSFUL JUMPS

The distribution of scores for %SJ was even more limited than that of %AJ, with a total range of 67.00 – 100% and a mean of 97.48%. Further, of the 46 total sessions of testing, over half (28 sessions) showed a score of 100%. Finally, results of a Wilcoxon Signed Rank test showed no median differences in the overall %SJ scores between the loaded and unloaded conditions ($p = 0.553$). Given these results, the %SJ appeared to not be a useful measure of performance on the ACAT, and only descriptive statistics for the data were calculated and presented below (Figure 9).

Visual inspection of Figure 8 confirmed the lack of any apparent mean changes in %SJ between loaded and unloaded conditions, or any pattern of changes across exercise intensities.

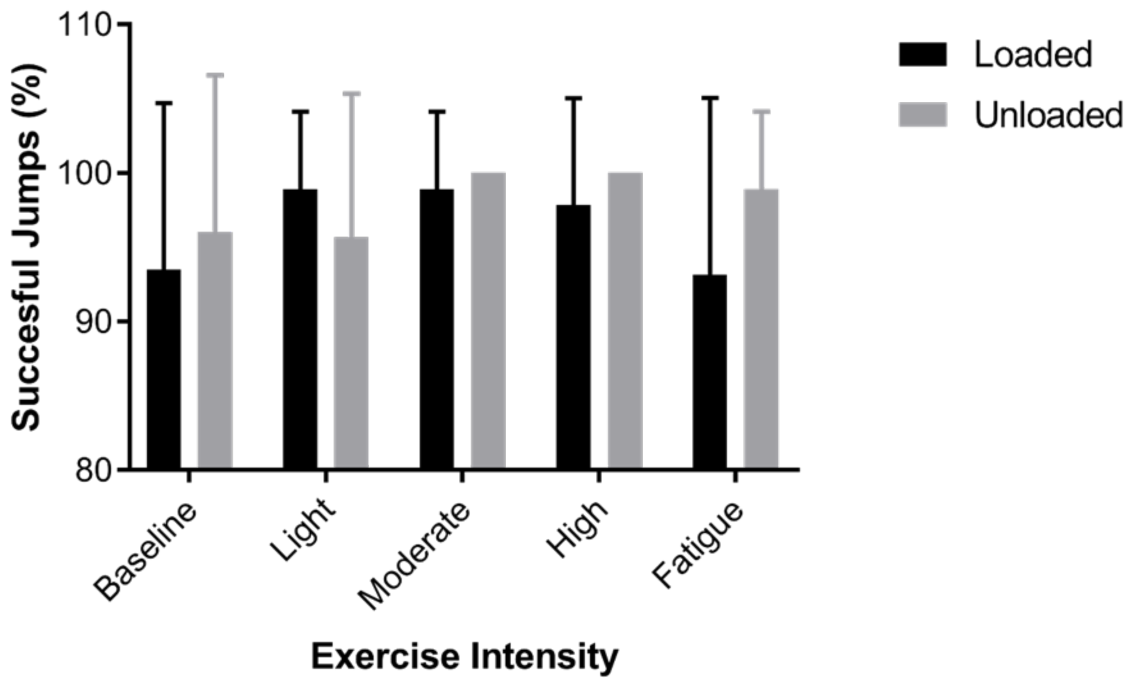

Figure 9: Mean successful jumps by exercise intensity and load carriage condition

- Error bars indicate 95% confidence intervals; groupings without error bars indicate that the interval was too small to depict

4.5 EXPLORATORY ANALYSES

Results of the 2x5 mixed ANOVA for the effects of baseline %AJ grouping on RTs across exercise intensities showed no significant interaction of exercise intensity and %AJ on RT (F = 0.839, p =

0.504). However, there were significant main effects for both exercise intensity ($F = 19.964$, $p < 0.001$, $\eta_p^2 = 0.487$) and %AJ grouping ($F = 316.683$, $p < 0.001$, $\eta_p^2 = 0.938$). Pairwise comparisons showed a mean difference in RTs of -134.63 ms between participants scoring "poor" versus "good" for baseline %AJ ($p = 0.014$). Results of the 2x5 mixed ANOVA for the effects of post-fatigue %AJ grouping on RTs across exercise intensities showed similar results, with a non-significant interaction term ($F = 0.544$, $p = 0.704$) and a significant main effect of post-fatigue %AJ grouping ($F = 14.644$, $p = 0.001$, $\eta_p^2 = 0.411$). Pairwise comparisons showed a mean difference in RTs of -167.52 ms between participants scoring "poor" versus "good" for post-fatigue %AJ ($p = 0.001$). These effects are depicted in Figure 10, showing lower mean RTs across all stages of the IFP for participants classified as having "poor" %AJ at both baseline and post-fatigue.

Results of the repeated measures ANCOVAs revealed no significant relationship between RT across exercise intensities and either peak maximum jump distance or RFD. For maximum jump distance, the interaction term with exercise intensity ($F = 0.473$, $p = 0.499$) and the main effect ($F = 0.197$, $p = 0.661$) were non-significant. For RFD, these results were mirrored with both the interaction term ($F = 0.463$, $p = 0.504$) and the main effect ($F = 3.406$, $p = 0.079$) non-significant. Results of Mann-Whitney U tests showed no significant differences in either peak maximum jump distance ($p = 0.600$) or RFD ($p = 0.557$) between individuals categorized as performing "poor" compared to "good" for %AJ at baseline.

Finally, results of the 1x5 repeated measures ANCOVA showed no significant interaction of exercise intensity and maximum jump distance decrement on RT ($F = 0.004$, $p = 0.949$). However, there was a main effect of change in maximum jump distance ($F = 4.783$, $p = 0.039$, $\eta_p^2 = 0.188$). Pairwise comparisons showed a significant effect of jump distance decrement at the moderate ($t = -2.136$, $p = 0.045$, $\eta_p^2 = 0.178$), high ($t = -2.204$, $p = 0.039$, $\eta_p^2 = 0.188$), and fatiguing

($t = -2.258$, $p = 0.035$, $\eta_p^2 = 0.195$) intensities, with larger decrements related to higher RTs. There was still a main effect of exercise intensity ($F = 8.023$, $p = 0.010$), with the effect size also reduced ($\eta_p^2 = 0.276$) compared to the model without maximum jump distance decrement as a covariate. To depict the main effect of maximum jump distance decrement, participants were dichotomized into “large” and “small” decrement groups, based on a median split at 5.50 cm. Then, mean RTs by grouping for maximum jump decrement were plotted across exercise intensities. Figure 11 portrays the effect of this grouping on RTs, showing higher mean RTs across all exercise intensities for the large decrement group. Also notable are the lower bounds of the 95% confidence intervals for the small decrement group, showing much lower RTs (< 300 ms).

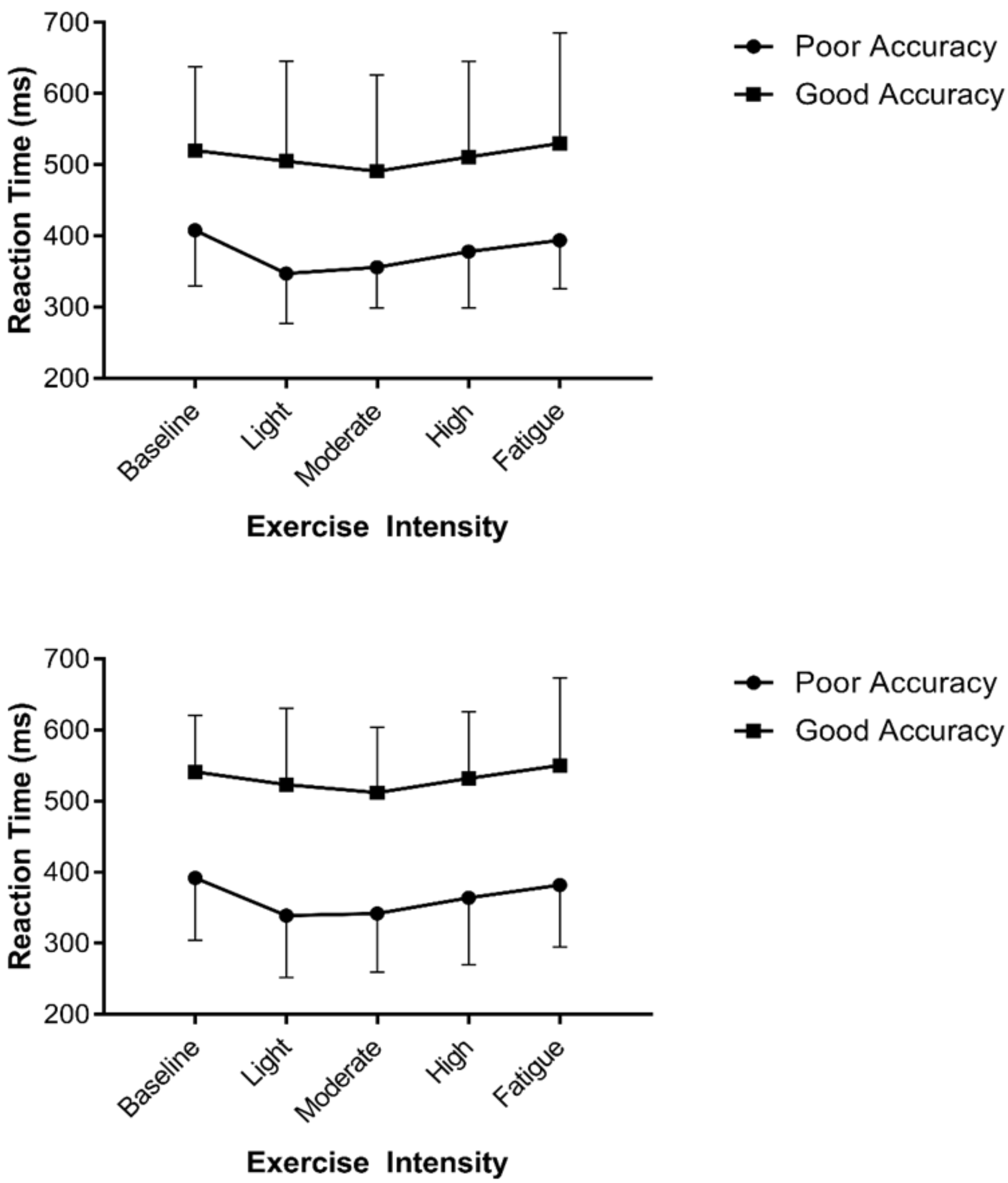

Figure 10: Main effect of judgement accuracy at baseline (top) and post-fatigue (bottom) on reaction times across exercise intensities

- ms = milliseconds

Figure 10 (continued)

- Error bars indicate 95% confidence interval upper (large decrement) and lower (small decrement) bounds

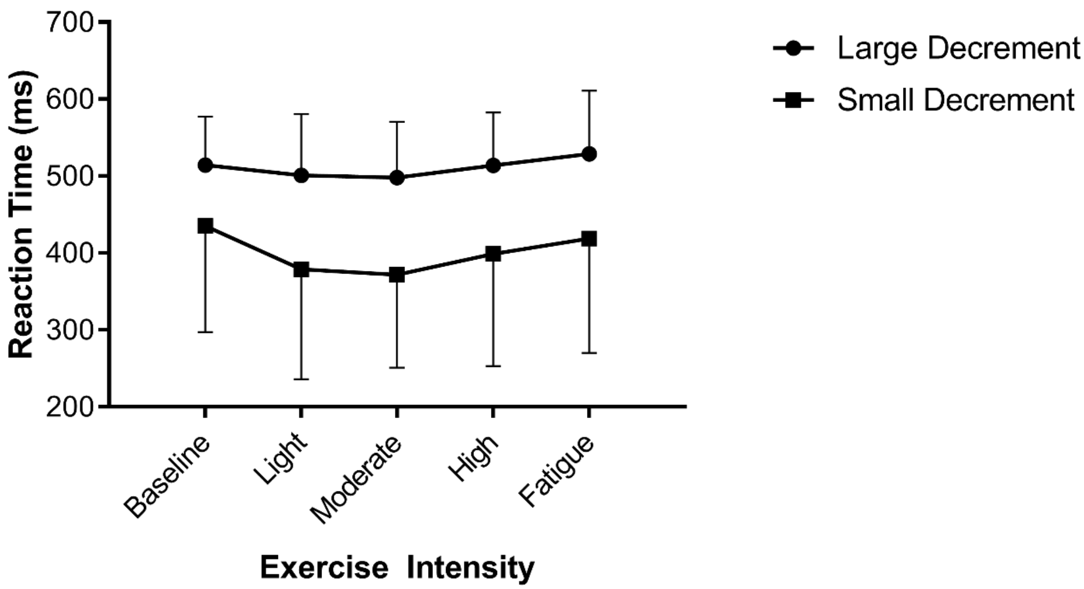

Figure 11: Main effect of maximum jump distance decrement on reaction times across exercise intensities

- ms = milliseconds
- Error bars indicate 95% confidence interval upper (large decrement) and lower (small decrement) bounds

5.0 DISCUSSION

A wealth of previous research has identified detriments to perceptual-motor (re)calibration through changes to environmental constraints, task constraints, or an individual's action capabilities. [8-14] However, literature on the effects of disruptions to an individual's action capabilities has either focused on the effects of artificial perturbations or perturbations that are not relevant to the majority of athletic populations.[10-12] Exercise-induced fatigue and load carriage are two variables that are much more relevant for occupational and competitive athletes. Further, previous literature has provided significant support for their effects on action capabilities[16-19,33,35-38], and tangential support for their possible effect on perceptual-motor calibration and motor control.[20-26,107] There have been a limited number of studies, with significant limitations in their methodologies, focusing on the direct effects of fatigue and load carriage on perceptual-motor calibration.[8,13,14,39] Further, no previous research has addressed the interactive effects of fatigue and load carriage, or the effects of incremental exercise intensities. Subsequently, the purpose of the current study was to examine the independent and interactive effects of incremental exercise, from low to fatiguing intensities, and load carriage on reaction times and judgement accuracy in response to an affordance-based task.

5.1 EFFECTS OF THE INCREMENTAL FATIGUE PROTOCOL

Overall, the results confirmed that the IFP was successful in producing a state of fatigue across the sample. The mean maximal heart rate that was achieved was 192 bpm, an average of 98.6% of participants age predicted heart rate max. Both values are indicative of fatiguing intensities of exercise and similar, or higher, than previously reported values from incremental, fatiguing bouts of exercise.[20,21,23,149] The mean maximal RPE value that was attained was 19.54, indicative of maximal exertion based on the range of the scale (6 – 20) and previous literature.[19,21,104,134,135] On average, subjective ratings of fatigue, assessed by the POMS, increased by 16.22 from pre- to post-fatigue measurements, and the mean post-fatigue POMS score was 17.78. Summarily, the IFP induced a change in fatigue equal to 81.1% of the total scale (0 – 20) and higher than those reported in previous literature.[138] Further, means for the maximal rating of fatigue reached, or post-fatigue, were significantly higher than trait levels (Mean = 5.8 – 10.7) reported in similar cohorts.[137]

Finally, the results showed significant mean decreases in both jump distance (-7.96 cm) and RFD (-802.10 N/sec) during maximal horizontal jumps from peak to post-fatigue measurements. As a percentage of mean peak values, this represents a ≈ 5% and 21% change in max jump distance and RFD respectively. Comparisons with previous literature for both are difficult, due to a lack of studies reporting on RFD decrements with incremental fatigue and the majority of studies reporting on decrements in jump distance/height using a threshold of the decrement as the termination criteria for their fatigue protocol.[19,135,141] The decreases in jump distance are slightly lower than those reported by Collins et al.[145]. However, given that both jump distance and RFD decreased significantly, and the decreases in RFD showed a medium effect size, there is sufficient evidence to conclude that the IFP affected anaerobic performance.[150] In addition, the significant reductions in both jump distance and RFD indicate that the IFP was successful in perturbing the action capabilities of participants, which is central to the purpose of investigating the effects of fatigue on perceptual-motor calibration. In conclusion, fatigue was confirmed by a comprehensive review of both objective and subjective measures.

5.2 SPECIFIC AIM 1: EFFECTS OF FATIGUE AND LOAD

5.2.1 Fatigue

Independent of load carriage, fatigue was found to have a significant effect on RTs, but not %AJ during the ACAT task, partially supporting the hypotheses for Specific Aim 1. Reaction times were found to be significantly higher (worse) post-fatigue compared to moderate intensity exercise.[150,151] Comparisons with previous research are difficult, as only one study has assessed the effects of fatiguing exercise on an affordance-based task. These results are partially in line with those of Pijpers et al.[13], who also reported no changes in the accuracy of maximum reaching height judgements after a fatiguing bout of exercise. However, given the significant methodological limitations in the Pijpers study discussed previously, these results provide more concrete evidence that fatiguing exercise does not appear to affect the accuracy of action boundary judgements, in healthy, young adults.

More importantly, the current study is the first to report on the effects of fatigue on RTs in response to an affordance-based task. One previous study by McMorris et al.[20] did report reaction and movement times, however the authors utilized a psychomotor task, absent of any perceptual-motor component. Despite this, the results of the current study are in line with those of McMorris et al.[20], who reported significant deficits in both reaction and movement times after a fatiguing bout of cycling exercise compared to measurements taken after a bout of exercise at a moderate intensity (70% of maximum intensity). In contrast to the current study, the authors also reported significant increases in RT compared to baseline measurements.[20] In the current study, RTs were not significantly increased post-fatigue compared to baseline measurements, and on average, were actually fairly similar (Baseline Mean (ms) = 476, Post-Fatigue Mean (ms) = 477). Comparative to the McMorris study, this may be explained by the differences in tasks used to measure RTs, however it is difficult to confirm this without more conclusive evidence (i.e. a larger body of research) on affordance-based tasks and fatiguing exercise.

Regardless, the significant increases in RTs comparative to the moderate intensity stage demonstrates that during fatiguing exercise, accuracy of judgements may simply be maintained by decreasing the speed at which perceptual-motor judgements are made. This is an important finding for previous research on perceptual-motor calibration and recalibration. Much of this previous research has demonstrated full and rapid recalibration to an individual's action boundaries in response to changing action capabilities or environmental/task constraints.[44,56,64-66,68] However, these results show that individuals may not be fully recalibrated to their action boundaries simply because their perceptual-motor judgements are accurate. On a larger scale, they indicate the need to take a more comprehensive view of the behaviors surrounding perceptual-motor judgements, when making decisions on the extent to which an individual has recalibrated to their altered action boundaries.

From an applied perspective, these results may hold a variety of implications. A delay in a given movement decision, even of the magnitude demonstrated in the current study, leads to the likelihood that the individual's available affordances will be significantly reduced, or at the least, altered. As discussed previously, athlete's operate in highly dynamic and fluid environments, where affordances are presented one moment and gone the next.[3] Indeed, the mean reported delays in RT after fatigue for the current study are larger (38 compared to 20 ms) than those previously reported to differentiate between highly developed athletes and individuals with no athletic experience.[152] This alteration to the array of available affordances with delayed reactions could potentially lead to an increased likelihood for either unsuccessful movements or the selection of risky movement behaviors in an effort to scale an action to the original movement demands.

While more research is needed to confirm that the delays in movement initiation translate to these outcomes, this applied perspective provides an important interpretation of the current study's results related to fatigue. Without this perspective, one could argue that the trade-off between %AJ and RT indicates that participants successfully recalibrated to their fatigued state, given that %AJ was maintained by delaying RT. This argument holds significant merit within the context of the affordance task, given that the endpoint of the task was a single movement decision. However, based on the application of these results outlined in the previous paragraph, we would counter than one must consider the impact of delayed action for an initial movement on the availability of subsequent affordances for action. In this sense, again, a more holistic view of perceptual-motor calibration must be taken, where the behaviors around successful judgements of affordances are considered as important as the accuracy of judgements themselves. It is also worth noting that participants were instructed to make their decisions as accurately **and** quickly as possible. Therefore, increases in RT could be considered an indication of inadequate recalibration, even within the context of the ACAT task, given that one of the task constraints was related to reacting as quickly as possible to the presented marker.

Finally, the exploratory analyses demonstrating a significant effect of %AJ on the relationship between exercise intensity and RT, provides more support for the notion that there was a trade-off between movement initiation and judgement accuracy. Summarily, the results showed that individuals who were "poor" performers for %AJ, at both baseline and post-fatigue measurements, demonstrated significantly lower RTs across all stages of the IFP. Furthermore, %AJ grouping showed a large effect size in both mixed ANOVAs ($\eta_p^2 > 0.25$)[150,151], although the main effect of exercise intensity remained significant. However, caution should be used in the interpretation of these results, given that this was an exploratory analysis that the current study was not designed or powered for.

5.2.2 Load Carriage

In contrast to fatigue, no significant effect of load carriage on either RTs or %AJ was detected, also counter to the hypotheses for Specific Aim 1. Qualitatively, it did appear that mean RTs were slightly longer (≈ 15-19 ms) and mean %AJ was consistently lower (≈ 3-4%), both at baseline and across most stages of exercise. However, these differences were not statistically significant. These results are consistent with previous studies assessing the effects of load carriage on judgements of maximum jumping-reach height and horizontal jumping.[39,64] However, these studies utilized loaded conditions of 5 – 10% BW, therefore the current study adds to these previous findings by demonstrating adequate recalibration to a magnitude of load more relevant for occupational athletes. In addition, our results indicate that reactions were not simply delayed in the loaded condition to maintain judgement accuracy.

In contrast to our findings, several studies have reported deficits in either judgement accuracy or RTs on affordance-based tasks.[8,14] In one of these cases, the differences in findings may be attributed to the differences in the tasks used to assess perceptual-motor judgements (body-scaled vs action-scaled).[14] However, this previous study by Petrucci et al.[14] also lacked a control condition, presenting a more likely explanation. The previous study may have found the observed deficits in judgement accuracy to be normal, as in the current study, if the authors had compared them to judgements in an unloaded condition.

The divergence in findings that is more difficult to explain comes from the second study, by Palmer et al.[8]. In this study, the authors reported deficits, induced by load carriage, in both RTs and accuracy on a marksmanship task following a drop-landing.[8] These effects were also found to be graded, with increasing magnitudes of load (Mean normalized loads = 2.5, 30.1, and 45.2% BW) inducing greater deficits. These findings present the best comparison to the current study, given the use of similar magnitudes of load and an action-scaled task that is at least relevant for several sectors of occupational athletes (military/police). One explanation for our divergent findings may come from the dual-task paradigm utilized by Palmer et al.[8], with participants required to perform a movement task and then immediately react to the marksmanship task. Given that movement tasks during real-life scenarios for athletic populations are often coupled in a similar nature, where the execution of one movement at least partially determines subsequent affordances for movement, this explanation presents an interesting line of future research.

The vast-majority of affordance research has utilized measures with a single-task paradigm, as the current study did. Although more research is needed, the conflicting reports of the current study and Palmer et al.[8] provide evidence for the need to increase the complexity of these tasks in an effort to make them even more ecologically valid. Although there are pragmatic concerns regarding this, recent studies have begun to utilize virtual reality in the assessment of perceptual-motor judgements.[56,65,153-155] This modality would seem to present an exciting opportunity to develop measures that match the demands of the athletic environments, affordance-based tasks. Further, these new measures would open lines of research into the effect of adding these layers, and the true ecological validity of previously used perceptual-motor tasks.

While a more complex task may yield differing results, the current study presents evidence that load carriage, up to 30% BW, does not have a significant effect on perceptual-motor calibration for healthy, young individuals. Therefore, it may be that load carriage is not a significant enough perturbation to cause perceptual-motor deficits in this population, and therefore not an effective modality in studying the process of recalibration in this task. Another possibility is that the magnitude of load (30% BW) was not enough to provide an adequate perturbation. Future research should focus on the effects of higher magnitudes of load (30-50% BW), as it is plausible that higher loads, yielding a greater reduction in action boundaries, would provide a more significant challenge for perceptual-motor recalibration.

5.2.3 Interaction of Load and Fatigue

Similar to the independent effects of load carriage, our results did not support the hypotheses for the interaction of fatigue and load carriage on either RTs or %AJ. While mean %AJ declined from baseline to post-fatigue measures slightly in the loaded condition (≈ 2%), and increased slightly in the unloaded (≈ 2%), the effect was non-significant. Further, this may have simply represented a speed (time)/accuracy trade-off, as RTs appeared to increase slightly in the unloaded condition (≈ 3 ms) and decrease slightly in the loaded (≈ 2 ms). This effect was also non-significant, and regardless of the statistical significance, the size of these effects were negligible.

While this was the first study to investigate this interactive effect, one study by Eddy et al.[100] did find an interaction effect of load carriage and fatigue on a cognitive choice-reaction time measure. Beyond differences in outcome measures, this can be attributed to differences in the study design, where the previous study had participants carry the loads while performing the fatiguing exercise.[100] Given the known effects of load carriage on physiological stress during exercise, one could argue that their results should be interpreted as the effects of increasing fatigue through load carriage, than the interaction of load carriage and fatigue.[33,35,122-126] In contrast, the design of the current study, where total exercise load was matched between the loaded and unloaded conditions, allows for the interpretation of our results as the true interaction of fatigue and load, or the additive effects of load on fatigue.

Despite having no direct comparisons in previous literature, these results were unexpected. With the previously discussed literature reporting a detrimental effect of similar loads on perceptual-motor calibration, we would have expected to see an additive effect of load carriage to the demonstrated effects of fatigue.[8,9,14] One possible explanation is that participants performed multiple blocks of the ACAT leading up to the fatiguing measurement. Subsequently, it could be argued that participants may have become calibrated to their action boundaries in the loaded condition before the fatiguing measurement, to the point where the effects of the additive weight were washed out. However, this is unlikely, given that participants received the same number of trials across sub-maximal stages of the IFP in the unloaded condition. A future study could be easily designed to confirm this, where only two blocks of perceptual-motor judgements are performed; one before and one after a fatiguing protocol.

5.3 SPECIFIC AIM 2: EFFECTS OF EXERCISE INTENSITY

The results of the current study demonstrated a significant effect of exercise intensity on RTs, with a large effect size ($\eta_p^2 > 0.25$).[150,151] This effect was quadratic in nature, with RTs decreasing through the light and moderate intensity stages, and then increasing again through the high intensity stage and fatigue. While these results are in line with the hypotheses for Specific Aim 2, the results for %AJ were not, showing no effect of increasing exercise intensity on judgement accuracy. While means for %AJ did appear to follow a similar pattern to RTs, increasing (≈ 3%)

through the moderate intensity stage and decreasing (≈ -2%) again through fatigue, this effect was not significant.

While no previous literature has reported the effects of increasing exercise intensity on an affordance-based measure, the results for RT mirror previous reports on both decisional cognitive and psychomotor measures. In decisional cognitive performance measures, this quadratic effect of increasing exercise intensity on RTs has been demonstrated across a plethora of studies, and has been termed the inverted-U hypothesis.[23,24,27-29,100-104] Across this research, the exact intensity at which RTs are reported to show peak improvements (bottom of curve) differs slightly (60 – 80% of maximal intensity), however the results of the current study fall within this range (60-70% of maximal intensity). [23,24,27-29,100-104] Further, much of this previous literature has also demonstrated similar results in the comparison of RTs at fatiguing intensities and baseline performance, where reactionary decrements are only seen in comparison to peak performance at moderate intensities.[23,25,26,115] Finally, while the extent of previous research on psychomotor measures and increasing exercise intensity is limited, the results of the current study are in line with both studies of this nature.[20,119]

The current study holds many similarities to this body of previous work, however it is the first to demonstrate the effects of increasing exercise intensity on an affordance-based measure, and therefore perceptual-motor calibration. This is an important distinction, given the previously discussed limitations in the real-world applicability of cognitive and pyschomotor measures, in holding with ecological theories of motor control. The improvements in RTs through light and moderate exercise are generally attributed to an "arousal" effect of non-fatiguing exercise.[10, 45] Several mechanisms have been proposed for this arousing effect, generally categorized into improvements in the central (increased catecholamine activity, increased cerebral blood flow, etc…) and peripheral/motor (increased mechanical compliance of muscles, increased excitability of motor synapses, etc…) components of a motor response.[99,101,106,108,109]

The results of the current study cannot speak to the mechanisms by which RTs were improved. In the context of cognitive and psyschomotor measures, it is likely that a combination of previously proposed factors results in the increased speed of responses. However, in the context of affordance-based tasks, these mechanisms would not seem to be as relevant. For example, it is likley that the mechanical compliance and excitability of the musculature used for jumping was improved with through the light to moderate stages of exercise, resulting in improved jump performance. This is an established effect of sub-maximal exercise[156,157], and further, some indirect evidence is provided for this by the improvements in maximal jump distance through sub-maximal stages. However, because the ACAT is an action-scaled task, the jump markers were adjusted based on these changes in maximal jump distance, indicative of changes in an individual's action boundary. Therefore, the ability to maintain or improve the speed of responses is still dependent on an individual being attuned to these alterations to their action capabilities, and the resultant alterations to the movement task.

Supporting this claim are the results from another of the exploratory post-hoc analyses, demonstrating that the decrement in maximum jump distance (peak to post-fatigue) had a significant effect on the relationship between increasing exercise intensity and RT. These results suggest that there was a direct mean effect of the magnitude of perturbation to an individual's action boundary/capabilities on the resulting improvements/deficits in RT. However, while the main effect of maximum jump distance decrement was significant, pairwise comparisons showed that there was only a significant effect from moderate to fatiguing intensities. Further, as mentioned previously, this was an exploratory analysis that the current study was not designed to address.

Similar to the results for the effect of fatigue on judgement accuracy, the current study found no effect of increasing exercise intensity on %AJ. While this is counter to our hypotheses, it is worth noting that %AJ was maintained, and so the improvements in RT through light and moderate intensities was not at the detriment of judgement accuracy. The most likely explanation lies in the high levels of perceptual-motor calibration noted at baseline providing a ceiling effect, with a mean of 90.2% for %AJ and over half of participants (58.2%) demonstrating 100% accuracy. This high attunement to an inividual's action boundaries has been widely reported in past literature, although the evidence has been more equivocal regarding action-scaled affordances.[13,43,48,49,54,55,57,58]

A second explanation lies in nature of the measure used, where judgement accuracy for each trial was dichotomous in nature (Accurate / Not Accurate) and only 6 responses were collected at each stage of the IFP. Several considerations went into the selection of the affordance-based task, namely previous literature demonstrating that action-based responses to affordance tasks yield faster reaction times and more accurate judgements.[55,58-60] Further, the number of trials was limited to the minimum necessary to obtain reliable and stable responses over repeated testing, in an effort to minimize the amount of testing time between stages of the IFP. It may be that the lack of an effect on %AJ was simply a result of the inherent resolution in our measure. In previous literature, many affordance measures have been described where judgement accuracy is assessed as a continuous variable, as the magnitude of error in the judgement of a given action boundary.[43,45,48,58,64,67]

Therefore, it would seem that future research is needed, focusing on the development of affordance-based measures that keep with the above considerations, but also provide a continuous outcome with higher resolution. One such improvement may be in shifting the representation of the action boundary from a static one (i.e. set jump marker) to a dynamic one (i.e. moving jump marker). In this way, it would still be possible to have an action-based response for affordance judgements, but obtaining a continuous measure of judgement accuracy. Another possibility is in moving the measure to a virtual reality environment, where greater automation would be afforded (e.g., jump marker wouldn't have to be manually reset, participant wouldn't have to reset to starting position). This would allow for the collection of more trials in a similar amount of time, effectively increasing the resolution of the measure. Finally, it is worth restating that the sample consisted of young, healthy and active individuals, therefore it may be that either the intensity of work or total workload imposed on the sample was not sufficient to perturb their perception of their action boundaries or capabilities.

5.4 LIMITATIONS

The current study holds several limitations, outside those discussed in previous sections, that should be recognized. The first is related to the characteristics of the sample, affecting the generalizability of our results. We focused our recruitment on participants that were young, healthy and highly active, as the study was focused on the effects of two variables, fatigue and load carriage, that are relevant for competitive and occupational athletes. Therefore, caution should be used when generalizing the results to populations without these characteristics. It is likely that their responses to exercise, especially through the higher intensities used in the current study, would differ significantly. Second, we did not obtain kinematic measures to quantify the movement strategies used by participants to complete the ACAT. This was due to pragmatic concerns, related to attempting to have participants perform the IFP while wearing reflective markers and increased time added to blocks of ACAT trials to allow for kinematic assessments. Several previous studies have demonstrated alterations to movement strategies during an affordance-based task, in response to load carriage.[8,9] Therefore, it may be that while reaction time and judgement accuracy were not affected by load, these perturbations to perception-action coupling were not captured.

Another limitation is that the stages of the IFP were set based on each participant's age-predicted maximum HR. While age-predicted maximum HRs are fairly accurate in younger adults and at a population level, it is not an exact measurement of maximal heart rate on an individual basis.[158] However, one could argue that the errors in the prediction of true maximal heart rate would most likely even out across the sample (i.e. some higher, some lower). Further, the mean observed maximal heart rate from the final stage of the IFP, expressed as a percentage of the predicted maximal heart rate (98.62%), supports this argument.

Finally, while trials of the ACAT were initiated immediately following the end of the fatigue protocol, it is likely that participants began to recover in the time it took to complete trials. While this does limit the interpretation of the effects of fatigue on the outcome variables, we would submit that this is a natural limitation of almost any study addressing the effects of acute fatigue. We know that these effects are transient, and therefore any measure that cannot be performed during exercise, which includes most measures of interest, will allow for some form of recovery time while they are being performed. This raises an interesting consideration for future research, as it may be that a measure of perceptual-motor control can be developed which can be integrated with an exercise protocol, and therefore eliminate these effects. One possibility is in the use of a Computer Assisted Rehabilitation Environment System, which integrates a virtual reality environment with a treadmill.

5.5 CONCLUSIONS

In summary, the current study demonstrated increases in RT to an affordance-based task in response to fatiguing exercise, however no effect was observed on the accuracy of action-boundary judgements. These results point towards a trade-off between the speed and accuracy of responses during fatigue. The increases in RT could be interpreted as an adjustment to a fatigued state in order to maintain judgement accuracy, and therefore that participants succesfully recalibrated. However, in the context of an occupational or competitive athlete's operational environment, this delay in the initiation of a movement response has the potential to limit available affordances for movement, resulting in increased risk for collisions, risky movement behaviors, and unsuccesful movement outcomes related to performance. Further, the constraints of our affordance task were set so that the accuracy and speed of responses were to both be considered by participants when performing their trials. We would therefore conclude that the increases in RT induced by fatigue are indicative of at least decreased performance on the affordance task, and possibly, inadequate perceptual-motor recalibration. However, further empirical evidence would be needed to confirm this interpretation of our results related to fatigue.

The current study also demonstrated a significant, quadratic effect of increasing exercise intensity on RT to an affordance-based task, whereby times improved through moderate intensities, and declined through high intensities and fatigue. With the accuracy of judgements also being maintained through sub-maximal intensities, the results indicate improved perceptual-motor recalibration with light and moderate intensity exercise. Finally, no effect of load carriage, independent or as an interaction with fatigue, was detected on either RT or judgement accuracy. Therefore, it may be that the magnitude of load, or that load carriage itself, is insufficient to perturb perceptual-motor calibration in this population.

These results would seem to hold great significance, for both researchers and clinicians alike. In combination, they demonstrate performance on a perceptual-motor task can be successfully perturbed by fatiguing exercise, presenting as increases in the time taken to initiate a movement decision. Given these effects, future research can focus on whether these perturbations are associated with, or predictive of, behaviors or events that are also thought to be affected by fatigue in athletic populations (i.e. risky decision making, musculoskeletal injury, performance decrements). As previous research has demonstrated that individuals show high levels of perceptual-motor calibration in optimal conditions, it may be that these outcomes would be more associated with the ability to preserve perceptual-motor judgements and response times in a perturbed state.

Our results further demonstrate that these increases in RT begin to occur when exercise exceeds a moderate intensity (60-70% of HRR). For researchers, this provides evidence for the use of an adequate warm-up when an action-scaled affordance task (e.g., maximum jump-reach height, catchability of a ball, etc.) is being assesssed, in obtaining a true, “optimal” baseline measurement. For clincians, this provides further justification and guidance for tracking deficits in their athletes during practice or competition, using technologies that are easily implemented. In these regards, future research is still needed to confirm that the observed threshold for perceptual-motor calibration results in deficits in actual performance, however our results provide preliminary evidence to support this practice.

APPENDIX A. COMPLEMENTARY FIGURES FOR STATISTICAL ANALYSES

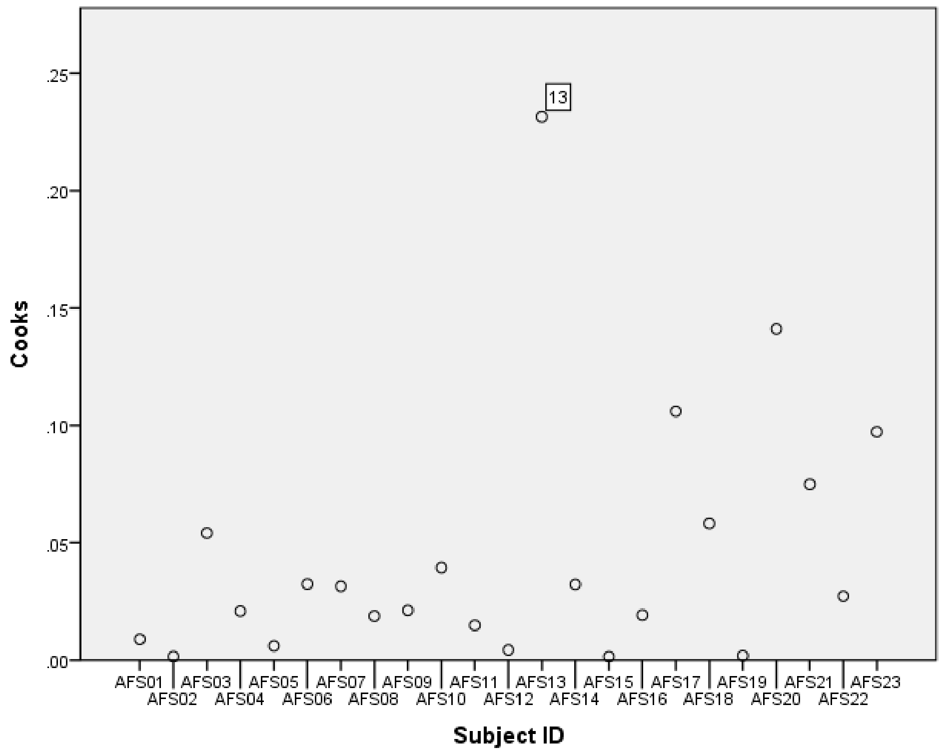

Figure 12: Cook's distance values for 2x5 ANOVA testing mean differences in reaction time by exercise intensity and load carriage

- Outlier marked with subject ID 13

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