THE RELIABILITY AND VALIDITY OF THE CATAPULT SPORT'S VECTOR ELITE 2.1 HEART RATE MONITOR

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ABSTRACT

Heart rate monitors are commonly used in sports with a large aerobic emphasis to monitor exercise intensity. Female athletes who participate in endurance sports such as field hockey and soccer are also at an increased risk for experiencing training maladaptation (Schwellnus, 2016). Wearable technology is utilized by practitioners to monitor athlete training characteristics. Catapult Sports has combined GPS technology and heart rate monitors to increase the utility of their garments. Catapult Sports's GPS component has been deemed valid and reliable (Varley 2012). However, the heart rate monitor has not been investigated by a third party. Therefore, the purpose of the study was to assess the reliability and validity of the Catapult Sports's Vector Elite 2.1 heart rate monitor in female athletes. It was hypothesized that the Catapult Sports' Vector Elite 2.1 heart rate monitor would exhibit good intra-device reliability (ICC = at least 0.7) during rest, moderate and vigorous exercise intensities. It was also hypothesized that the Catapult Sports' Vector Elite 2.1 heart rate monitor measurements during rest, moderate and vigorous exercise would exhibit a Pearson correlation of at least 0.7 when compared to a single-lead EKG. There would be minimal bias within 95% limits of agreement. Additionally, an acceptable coefficient of variation of 5-10%. A total of 27 division I female field hockey (n=17) and soccer (n=10) were recruited. Participants performed two VO_2max tests while wearing the Catapult garment and a single lead EKG to obtain maximum and average heart rate values for each test stage. Overall, the reliability of the heart rate monitor decreased at intensity decreased. The Catapult garment was not valid as intensity increased. Overall, the Catapult heart rate measurements displayed good accuracy during resting conditions and stage one but lost accuracy as intensity increase.

TABLE OF CONTENTS

INTRODUCTION

Across all divisions, there are over 520,000 student athletes competing in the National Collegiate Athletic Association (NCAA) and 226,212 of those athletes are female (NCAA Sports Sponsorship and Participation Rates Report, 2022). According to those statistics, female athletes make up half of the population participating in NCAA athletics. However, it has been established that females are underrepresented in sport and exercise science research (Cowely et al., 2021). Recently, authors reviewed 5,261 publications from sport and exercise journals. Of the publications, only 6% of the publications exclusively studied females, and 34% of the studies exclusively studied males (Cowely et al., 2021). It is necessary for researchers to pursue studies that are centered around females because the large gap in data has led to conclusions surrounding sport and exercise that are not applicable to females.

There are female sex characteristics that have an influence on the physiological response to exercise and athletic performance. Characteristics such as the menstrual cycle phases influence exercising heart rate (Mckinley et al., 2015) (Vallejo, Marquez, Borja-Aburto, Cardenas, & Hermosillo, 2005). In addition, the level of sports bra compression also influences performance and biomechanics of females during agility movements (McGhee & Steele, 2020). It is also important to note that when female athletes are included, their sample sizes are smaller than their male counterparts Hermand, 2021) (Michos et al., 2021). Overall, it is important to expand upon research that is exclusively performed on females.

Female athletes who participate in endurance sports such as field hockey and soccer are also at a greater risk for experiencing training maladaptation than their male counterparts (Schwellnus, 2016), putting them at greater risk of injury. In female athletes, overtraining and undereating can aggregate and result in conditions such as relative energy deficiency or female athlete triad. A symptom of the conditions includes decreased maximal heart rates after increased training (Meussen, 2013). Researchers have suggested monitoring heart rate during resting and training conditions to increase the ability to detect these conditions (Hedelin, 2000). Therefore, utilizing heart rate monitors could be beneficial for female athletes that participate in endurance sports.

A variety of wearable devices have been introduced into the athletic performance space, including global/indoor positioning systems, heart rate monitors and accelerometers (Bourdon et al., 2017). Wearable devices have been utilized to quantify athlete workload, performance, muscle imbalances, and heart rate (Seshadri et al., 2021). Heart rate monitors are commonly worn in sports with a large aerobic emphasis to monitor exercise intensity (Gilman,1993). Exercise intensity can be determined by calculating different percentages of the maximum heart rate (American College of Sports Medicine, 2021). Prescribing and monitoring intensity is the most common use of heart rate for both training and rehabilitation purposes (Achten & Jeukendrup, 2003) (Foster et al., 2017), (Seshadri et al., 2021). Currently, in sport, athletes are wearing either chest or wrist-worn heart rate monitors. The Polar H10 is a chest strap that is valid and reliable in various exercise intensities (Hettiarachchi et al., 2019). Wrist-worn devices such as Apple Watches or Garmin have demonstrated reliability during low intensity exercise but lack validity as intensity increases (Chow & Yang, 2020). It has been suggested that validity and reliability of wrist-worn heart rate monitors are influenced by motion artefact and the type of exercise being performed (Nelson et al., 2020). Heart rate monitors are frequently used in sports with a large aerobic emphasis. However, it would be advantageous for heart rate assessment products to be combined with other forms of technology to provide more metrics on athletic performance such as speed, acceleration, and total distance (Almulla et al., 2020). Combining different wearable devices should be investigated to ensure their utility for athletes in different sports.

In response to the desire for more information, companies such as Catapult Sports have combined global positioning systems and heart rate monitors to increase the utility of their products. Catapult Sports provides a sports bra-like garment that holds the global positioning device, Vector. The Vector device has been deemed reliable and valid (Varley, 2011), (Hodder, 2020) and can quantify the external load of an athlete. In 2019, Catapult launched the "Vector Elite 2.1" garment that contains an EKG sewn into the lower band so that the device can monitor heart rate without a supplemental strap (Lemire, 2019). Since then, no research has been performed on the reliability or validity of the heart rate monitor by a third party. It is possible Catapult Sports have conducted research on the garment; however there are no published articles available. Therefore, if a program were to invest in wearable devices that include a heart rate monitor, it is important to ensure the device is capable of consistently and accurately measuring heart rate at varying intensities.

SPECIFIC AIMS

The specific aims of this study are as follows:

1. **Assess the reliability of the Catapult Sports' Vector Elite 2.1 heart rate monitor in female athletes at different exercise intensities.**
    a. It is hypothesized that the Catapult Sports' Vector Elite 2.1 heart rate monitor will exhibit good intra-device reliability (ICC = at least 0.7) during rest, moderate and vigorous exercise intensities.
2. **Assess the validity of the Catapult Sports' Vector Elite 2.1 heart rate monitor in female athletes at different exercise intensities.**
    a. It is hypothesized that the Catapult Sports' Vector Elite 2.1 heart rate monitor measurements during rest, moderate and vigorous exercise will exhibit a Pearson Correlation of at least 0.7 when compared to a single-lead EKG. There will be minimal bias within 95% limits of agreement. Additionally, there will be an acceptable coefficient of variation of 5-10%.

LITERATURE REVIEW

Monitoring Heart Rate in Sport

There is abundance of research on the use of heart rate monitors in sport. Heart rate is categorized as an internal metric that is often assessed in athletes who participate in endurance sports (Foster et al., 2017), (Seshadri et al., 2021). This is because of the linear relationship between VO_2max and heart rate (Schantz et al., 2019). Monitoring heart rate is common practice during aerobic exercise to monitor intensity (Gilman,1993). Multiple heart rate metrics are monitored by practitioners; however, monitoring intensity is the most important application of heart rate monitors in sport (Achten, 2003). Exercise intensity is defined as the amount of energy expanded per minute to perform a certain task (Jeukendrup,1998). Heart rate can be used as a method to determine intensity during aerobic exercise. The American College of Sports Medicine provides multiple methods that utilize heart rate to calculate intensity during aerobic exercise. (ACSM,2021). Heart rate reserve (HRR) reflects the difference between an individual's maximal heart rate and their resting heart rate. Intensity can be calculated by assigning a target heart rate zone (THR). The equation for the HRR method is, THR = [(HRmax – HR rest) x % intensity desired] + HR rest (ACSM, 2021). Another way to prescribe exercise intensity using heart rate is through the heart rate method. The heart rate method equation is HR = HR max x % intensity desired. The equations used to prescribe intensity should be performed twice because intensity is typically described as a range. Maximal heart rate is often included in the equations. There are multiple ways to estimate maximal heart rate. The Fox formula, (220-age) is commonly used to predict maximal heart rate. However, this simple equation can overestimate, and underestimate measured heart rate max and therefore is no longer recommended (Tanaka et al., 2001). The Tanaka equation has shown a strong correlation to measured maximal heart rate in a large, diverse population (Camarda et al., 2008). Therefore, the Tanaka equation is more suitable than the Fox formula.

In summary, heart rate monitors are often used in sports with a large aerobic emphasis. This is because heart rate can be used as a tool to estimate intensity during aerobic exercise. There are multiple ways to use heart rate to estimate intensity, and there are influences that impact the ability for these estimations to be used universally. Lastly, there are heart rate metrics such as heart rate variability that have sparked interest in sports scientists because of their potential to evaluate an athlete's ability to respond to stress. However, researchers have yet to reach consensus regarding the usefulness of heart rate variability because of inconsistencies in the literature. Regardless, monitoring heart rate is an important tool to estimate intensity of aerobic exercise.

Reliability of heart rate monitors

Heart rate monitoring has become increasingly popular among athletes and coaches for monitoring and optimizing training and performance (Seshadri et al., 2021). The utilization of heart rate and wearable devices allow for real-time feedback on key athletic metrics. Reliability studies are necessary to ensure that heart rate monitors are consistent in measuring heart rate during exercise.

There are different forms of reliability that are assessed for activity trackers. These include intra-device and inter-device reliability (Evenson, et al., 2015). Intra-device reliability involves the test-retest results indicating consistency within the same tracker. Inter-device reliability indicates consistency across the same brand/type of tracker measured at the same time and worn in the same location. The protocol for assessing the reliability of heart rate monitors involves repeated testing sessions that are identical to each other. For heart rate monitors the protocols typically consist of performing a range of activities. The activities include resting, light, moderate and vigorous aerobic exercises (Schaffarczyk et al., 2022), and can be performed through walking, running, and cycling (Climstein et al., 2020) (Khushhal et al., 2017). It is important that for reliability studies that the protocol is repeated in identical conditions.

Intraclass correlation coefficients (ICC) are often utilized in reliability studies (Evenson et al., 2015). ICC is calculated as a ratio ICC = (variance of interest) / (total variance) = (variance of interest) / (variance of interest + unwanted variance) (Liljequist et al., 2019). If an ICC has a value below 0.5 the method is deemed poor. On the other hand, ICC values above 0.8 or 0.9 are often regarded as a sign of excellent reliability (Liljequist et al., 2019) (Koo & Li, 2016).

The reliability of multiple heart rate monitors has been assessed. There are many studies on the reliability of wrist-worn devices such as Apple Watch and Polar. One study that examined intra-device reliability of the Apple watch showed an improvement of reliability with an increase in exercise intensity from walking 5kmh (ICC=0.84) to running 10kmh (ICC=0.92). (Khushhal et al., 2017). Researchers examined the test-retest reliability of the Polar Vantage M Sports Watch during a Bruce protocol treadmill stress test. The device showed moderate to excellent reliability during Bruce Protocol stages 1, 2 and 5 demonstrated good to excellent test–retest reliability (0.78, 0.78 and 0.92). The Polar Vantage Sports displayed ICC values indicated poor to moderate reliability 0.42, 0.68 and 0.58 during rest, stage three and stage four of the Bruce protocol. (Climstein et al., 2020). The reliability of the Polar Vantage M Sports displayed a wide range of reliability during the Bruce protocol stages.

Overall, reliability studies require identical protocols that involve a range of intensities. Intraclass correlation coefficients are most often utilized to determine reliability of devices.

Reliability measurements need to be accompanied with validation analysis because a device cannot be reliable without being valid.

Validity of Heart Rate Monitors

Heart rate monitors are commonly used during sport to monitor the intensity of exercise (Gilman, 1993). Prescribing and monitoring intensity is the most common use of heart rate for both training and rehabilitation purposes (Achten & Jeukendrup, 2003) (Foster et al., 2017), (Seshadri et al., 2021). For a heart rate monitor to be useful in these practices, it is necessary for the heart rate monitor to provide accurate readings. Therefore, an important aspect to assess when examining a heart rate monitor is its validity.

Validity is defined as the extent to which an instrument measures what it is supposed to measure and performs as it is designed to perform (Fuller et al., 2020). The protocol for assessing the validity of a heart rate monitor involves comparing the device to a criterion reference. The electrocardiogram (EKG) is the gold standard that is utilized as a reference during validation studies on wearable heart rate monitors (Müllen, 2020). A single-lead EKG can be utilized as a criterion reference (Antonicelli et al., 2012). Multiple studies have utilized single-lead EKGs to compare the agreement of wrist worn and chest strap heart rate monitors. (Pasadyn et al., 2019) (Hajj-Boutros et al., 2023) (Hettiarachchi et al., 2019). The protocols for heart rate monitors involve participants performing activities while sitting, walking, running, and performing resistance exercises (Hajj-Boutros et al., 2023). Protocols for heart rate monitors also utilizing ergometers like treadmills or cycles. However, free-living conditions are also frequently used to assess validity of the device (Müllen, 2020). In summary, the protocol for a validation study requires the device to be compared to a criterion reference. In heart rate monitor validation studies, a single-lead EKG can be utilized as a criterion reference.

When assessing the validity of a heart rate monitor, the analysis of accuracy utilizes different statistics. The following statistics are utilized to assess the accuracy of a device to the criterion reference: Pearson correlation, coefficient of variation (CV) and Bland Altman analysis (Mühlen et al., 2021). The Pearson correlation describes the direction and strength of the linear relationship between two continuous measurements under assumption of normal distribution of two variables (Odom & Morrow, Jr., 2006). It is generally recognized that a validity estimate needs to be between 5-10% to be at an acceptable level (Baumgartner et al., 2003). The CV (%) indicates the accuracy of the estimate by examining the variability in relation to the mean. The most common use of the coefficient of variation is to assess the precision of a technique. It is also used as a measure of variability when the standard deviation is proportional to the mean, and to compare variability of measurements made in different units. Interpretation of the CV values follow these guidelines; CV% of 10%: poor accuracy; 5-10%: acceptable accuracy; < 5%: high accuracy (Hajj-Boutros et al., 2023). Mühlen et al., described the aspects of Bland Altman analysis. Bland Altman analysis evaluate the extent of agreement between the devices and the criterion method. The calculated estimates of mean difference and the Limits of Agreement (LoA) for the mean difference should always be accompanied with 95% confidence intervals (Cis). The acceptable accuracy expressed as mean difference (bpm) or percentage difference between the criterion measure and the index device may vary and needs to be evaluated individually considering the factors described above. The LoA for the absolute or relative difference are expected to contain 95% of paired differences for each measurement point by the two methods.

The validity of wrist-worn and chest strap heart rate monitors has been examined (Hajj-Boutros et al., 2023). The validity of Apple Watch 6, Polar Vantage V, and Fitbit Sense were examined in five different physical activities including sitting, walking, running, resistance exercises and cycling. The Apple Watch 6 displayed the highest level of accuracy for heart rate measurement with a CV of less than 5% for multiple activities at different intensities. The Polar Vantage V showed acceptable accuracy for heart rate for walking and cycling as well as high accuracy for sitting, running and resistance exercises (CVs between 2.44- 8.80%). The Fitbit Sense has a higher accuracy for heart rate during activities with a higher intensity and poor accuracy during sitting (CV: 10.76%) (Hajj-Boutros et al., 2023). Another study showed that the Garmin Forerunner 235 yielded heart rate values that closely correlated with the criterion measure, suggesting that the Garmin Forerunner 235 measures are valid for tracking HR changes during rest, treadmill running at 8.7 km/h and 12.1 km/h, cycling at 150W and rapid arm movements. However, due to limited correlation, the results suggest that compared with the PL the Garmin Forerunner 235 did not provide valid measures for tracking changes in HR during treadmill walking at 4.8 km/h and cycling at 50W and 100W (Støve et al., 2019). Another study found that the Garmin Vivo smart heart rate exhibits good to excellent validity while running and cycling (ICC=0.80-0.92) however Bland Altman analysis shows that the device underestimates the average heart rate (Chow & Yang, 2020). Overall, there is large variability in the validity of wrist-worn devices during different excise activities.

Female Athletes in Research

There has been a rise in female participation in sport over the last 50 years. Title IX improved the societal and cultural views on female participation in sport (Cowley et al., 2021)**.** The rise in female participation is sport has not been met with the appropriate resources and opportunities, such as funding and media coverage (Senne, 2016). Female athlete representation in research is not equal to their male counterparts, leaving a large data gap between the sexes in exercise science and sport. The “Invisible Sportswomen” recently examined the gender inequities within sport research (Cowley et al., 2021). The authors described the underrepresentation of female athletes in research by comparing the number of studies that utilized male athletes exclusively versus female athletes exclusively. Their findings showed that out of 5,261 publications reviewed, 63% of studies included data from both sexes, 31% utilized males only and only 6% of studies exclusively studied females. The alarming difference between the populations also transferred over to the number of male and female participants in the studies. Of the 12,511,386 participants included in their analysis, 66% were male and 34% were female. The consequences of this data gap have led to broad assumptions in the sports domain. A large portion of the current sport and exercise science guidelines are based on studies with male participants (Sims & Heather, 2018). Research is significantly lacking in appropriate representation of female athletes’ physiological characteristics. It is important to note that the research performed on female athletes utilizes testing protocols that were validated on male populations (Mujika & Taipale, 2019). Traditionally, researchers thought that the physiological responses to exercise did not differ between men and women, with men being viewed as adequate proxies for women (Bruinvels et al., 2016). However, it is known that biological sex is an important variable that influences the physiological response to exercise. The gap in data has negative effects on the perspective of female athlete research. Obtaining data on female athletes is crucial to improving their experience and athletic performance.

A research area of importance involves the influence of the menstrual cycle on female athlete’s athletic performance. The menstrual cycle averages 21-35 days and consists of four different phases (Mayo Clinic, 2022). The phases include the menses, follicular, ovulation and luteal. The literature examining the impact of menstrual cycle phase on heart rate is inconsistent.

However, the quality of research will improve by acknowledging the impact ovarian hormones have on physiological function. Dole et al., suggest reporting menstrual cycle phases in research improves research methodologies by preventing a common oversight such as failing to control for participants with menstrual dysfunction. Overall, despite the lack of evidence on the menstrual cycle's impact on aerobic capacity, monitoring menstrual cycle phases ensures reliability and provides detailed description of participants.

Division I Field Hockey and Division I Soccer

Field hockey is a stick and ball team sport that is skill-oriented and involves intermittent high-speed running bouts. Competitive match play consists of two teams of 10 players categorized into defenders, midfielders, forwards, and goalkeeper. Unlimited substitutions are allowed throughout the match as well. As of 2015, the match consists of four 15-minute quarters with a two-minute gap between each quarter and a 10-minute halftime. There are 79 Division I NCAA field hockey teams. Across all the divisions, there are currently 263 National Collegiate Athletic Association teams (NCAA, 2023). Research on field hockey is limited; however, there is evidence to suggest that the sport requires a large aerobic capacity (Reilly & Borrie, 1992).

There are studies that have utilized wearable devices to provide physiological descriptions of field hockey players during match and practice. McGuinness et al., (2017) outlined the average distance covered during match play as 5,530 meters. The total distance covered in a match is a combination of walking, jogging, and sprinting. High velocity speeds are covered in shorter distances when compared to moderate-intensity activities. (Gabbett et al., 2010; Lothian et al., 1994; Macutkiewicz et al.,2011). McGuinness et al., (2017) determined that most of the game is played at low-moderate intensity (88%), and a small portion of the match involves high-speed running (11%). Another study (Vescovi, 2015) described the speeds achieved during a field hockey match, and they defined low intensity 0.0-8.0 km/h. Moderate intensity was defined as 8.1–16.0 km/h. Lastly, high intensity was defined as 16.1-20 km/h. Based on these findings it is appropriate to state that field hockey requires well-developed aerobic capacity.

There are currently 347 NCAA Division I Women’s soccer programs. Majority of the programs will play roughly twenty games over the course of the regular season. In Division I women’s soccer the match consists of two, 45-minute halves. According to studies that have assessed match-play and positional demands, soccer requires athletes to have a large aerobic capacity. On average, field players will cover 10-12km during a match (Stølen et al., 2005). Throughout a soccer match, a high intensity movement such as sprinting, tackling, performing headers, will occur every 90 seconds running (Ekblom et al., 1986). There are also positional differences when assessing aerobic capacities. Ingrbrigsten et al., described the aerobic capacities of elite female soccer players. According to Ingribrigsten et al., defenders have a VO_2max of 51.85±5.05 ml/kg/min. Midfielders have a VO_2max of 55.36±5.65 ml/kg/min and attackers o 52.94±3.17 ml/kg/min. Lastly, goalkeepers have a VO_2max 50.70±4.96 ml/kg/min.

In summary, playing field hockey and soccer requires athletes to have a robust aerobic capacity and the ability to perform multiple bouts of high-speed running. Wearable devices have been utilized to describe the physiological profiles of both field hockey and soccer players. Internal and external metrics have been combined to enhance practice structure. Therefore, both field hockey and soccer programs could benefit from utilizing wearable devices that contain both global positioning systems and heart rate monitors. It is important to determine devices utilized by programs are reliable and valid for the metrics to be used to develop training strategies.

Catapult Sports in National Collegiate Athletic Association

Catapult Sports was officially founded in 2006 with the intention to enhance the performance of Australian athletes for the Sydney Olympics. Since then, Catapult has developed wearable technologies that were designed to address fundamental questions in sports performance. Catapult Sports is utilized by more than 3,800 elite teams in over 100 countries globally (Catapult, 2023). Currently, Catapult is used by every conference in the NCAA (Catapult, 2021). Catapult sports is a well-known brand that is invested in sports performance.

Catapult Sports has combined global positioning systems and heart rate monitors to increase the utility of their products. Catapult Sports provides a sports bra-like garment that holds the global positioning device, Vector T6. The Vector T6 device has been deemed valid when compared to Vicon Motion Systems (Varley, 2011), and accurately measured speed, and total distance covered during 80 running trials. However, another study by Crang et al., investigated the reliability of Catapult S7 during identical sprinting sessions. Crang et al determined that the Catapult S7 device varied from 0-37% during accelerations. In 2019, Catapult launched the “Vector Elite 2.1” also contains a heart rate monitor component. The Vector Elite 2.1 Vest has embedded heart rate sensors and uses conductive materials to channel the heart rate signal directly to the Vector device (Catapult, 2023). The heart rate monitor's sampling rate is 10Hz and is derived from the pickup pulses received from paired devices (Catapult, 2023). After the activity the data will be downloaded for further analysis.

Overall, Catapult Sports is utilized by many athletic teams and is deeply invested in sports performance. While there is varying support for the reliability of the GPS component, an investigation of the heart rate monitor is necessary.

METHODS

Participants

To achieve a moderate effect size ($d=0.5$ with $1-\beta \geq 0.8$) a total of 22 participants was required for the study. A total of 27 NCAA female athletes were recruited to participate in the study. The female athletes recruited were varsity members of field hockey (n=17) and soccer (n=10). The recruitment process involved contacting Michigan State University varsity athletes from the women's field hockey and soccer teams via email after receiving approval from coaching staff. The participants completed an informed consent, and a preparticipation screening was performed. The questionnaire utilized in the preparticipation screening was the American College of Sports Medicine's "Exercise Preparticipation Health Screening Questionnaire for Exercise Professionals". After the consent process and preparticipation screening, the phase of the participant's menstrual cycle was documented. Both documents were approved by the Michigan State University Institutional Review Board and methods were carried out in accordance with the relevant guidelines and regulations.

Protocol

The study consisted of two separate visits. The visits were scheduled so that both testing sessions took place during the same phase of the menstrual cycle and during the same time of day. The participants were instructed to refrain from caffeine and exercise for 24 hours before the testing session. Anthropometrics including height and weight were collected during both visits. Height was measured twice by using a stadiometer to the nearest tenth of a centimeter with the participants barefoot. The average of two measurements was used for analyses. Weight was measured in kilograms to the nearest tenth utilizing a manual weight scale. The average of the two measurements was used for analyses. The participants wore their same, assigned Catapult Sports Vector Elite 2.1 heart rate monitor as well as a single-lead EKG for both visits.

PowerLabs software was utilized for collecting EKG data. The electrodes were placed on the right arm (RA), left arm (LA) and left leg (LL). The RA electrode was placed under the right clavicle near the right shoulder within the rib cage frame. The LA electrode was placed under the left clavicle near the left shoulder within the rib cage frame. The LL electrode was placed on the left side at the lower edge of left rib cage.

The protocol consisted of performing two VO_2 max tests. The VO_2 max protocol consisted of four, three-minute stages. During the first stage the participant was lying supine for resting conditions. In stage two the participant performed aerobic exercise on a treadmill at 5km/hr (3.1 mph). Stage three consisted of an increase in speed to 10.2 km/hr (6.2 mph) and stage four increased to 12.5 km/hr (7.8mph). After stage four, the grade of the treadmill was increased by 3% every minute until volitional exhaustion. The speeds of the test were determined based on previous literature that described the average speeds achieved by field hockey players during competition (Vescovi et al., 2015). At least three of the following criteria needed to be met to determine VO_2max (ACSM, 2021): (1) Heart rate during the last minute exceeds 95% of the expected maximal HR using the Tanaka equation, (208 – (0.7 x age)). (2) Leveling off (plateau) of VO_2max, despite an increase in treadmill speed, $VO_2 < 150$ ml O_2. (3) A respiratory gas exchange ratio (VCO_2 / VO_2) at or higher than 1.1 was reached. (4) The subjects are no longer able to continue running despite verbal encouragement. Expired gases were collected. Expired gas analysis was performed using the Quark Cosmed system. The open spirometry system was calibrated before each measurement, as per the manufacturer's guidelines.

Statistics

Data analysis was performed utilizing SPSS statistical software. To analyze the test-retest reliability of the Catapult Sports's Vector Elite 2.1 heart rate monitor at different intensities intra-device reliability will be assessed by intraclass correlation coefficient (ICC). The average heart rate values for the last minute of each stage for VO_2max tests were compared to establish reliability. The ICC is a value between 0 and 1, where values below 0.5 indicate poor reliability, between 0.5 and 0.75 moderate reliability, between 0.75 and 0.9 good reliability, and any value above 0.9 indicates excellent reliability (Bobak et al., 2018). To analyze the validity of the Catapult Sports's Vector Elite 2.1 heart rate monitor at different intensities a Bland Altman test was performed along with Pearson Correlation and coefficient of variations. A validity estimate must be above 0.60 to be at an acceptable level (Baumgartner et al., 2003). Interpretation of the CV values follow these guidelines: CV% of >10%: poor accuracy; 5-10%: acceptable accuracy; < 5%: high accuracy (Hajj-Boutros et al., 2023). Bland Altman plots are used to estimate the agreement between measurements taken by two separate tools. Bland Altman plot analysis is a way to evaluate a bias between the mean differences of the second method compared to the first one (Giavarina et al., 2015). Heart rate values collected by the Catapult Vector 2.1 garment were compared to the values from the single-lead EKG. The average heart rate values for the last minute of each stage were compared to the reference standard through Bland Altman analysis and Pearson Correlation.

Heart rate measurements were deemed an outlier if they were greater or less than two standard deviations from the mean. When outliers measured by the EKG were identified, they were further analyzed. Heart beats detected by the EKG that were considered outliers were removed from the 1-minute section utilized for analysis. Outliers of the Catapult measurements for the entire minute were removed from analysis because the software does not provide the opportunity to view individual intervals between heartbeats.

RESULTS

A total of twenty-seven female participants were recruited. Three participants were dropped from the study due to sports injuries that were not related to participation in the study. Twenty-three participants completed both testing sessions, and twenty-four completed one. Table 1 shows participant characteristics, and Table 2 includes menstrual cycle phases of the participants with natural cycles during their testing sessions. Table 3 displays the number of participants taking a form of birth control. Of the participants on birth control, six participants were taking a triphasic oral form of birth control, two were on a monophasic oral form of birth control, and one did not report.

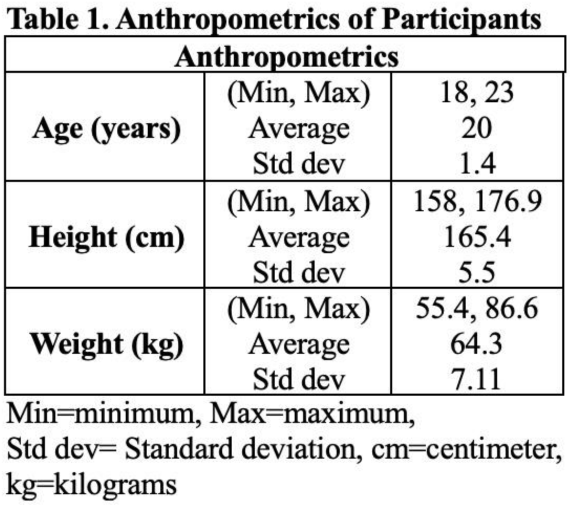


Table 1. Anthropometrics of Participants

Anthropometrics		
Age (years)	(Min, Max) Average Std dev	18, 23 20 1.4
Height (cm)	(Min, Max) Average Std dev	158, 176.9 165.4 5.5
Weight (kg)	(Min, Max) Average Std dev	55.4, 86.6 64.3 7.11

Min=minimum, Max=maximum,
Std dev= Standard deviation, cm=centimeter,
kg=kilograms

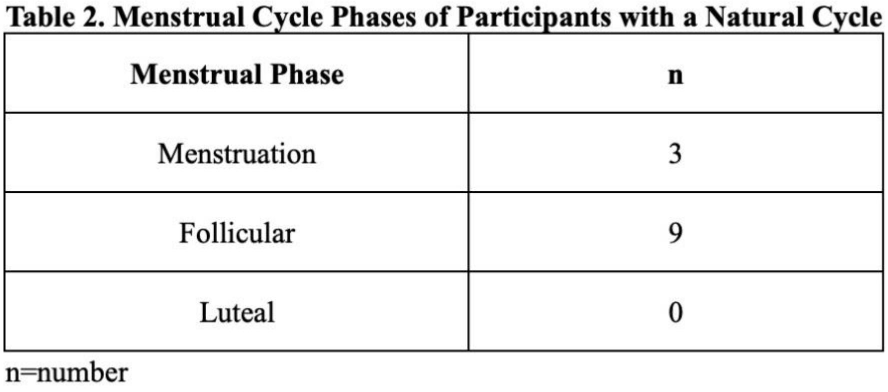
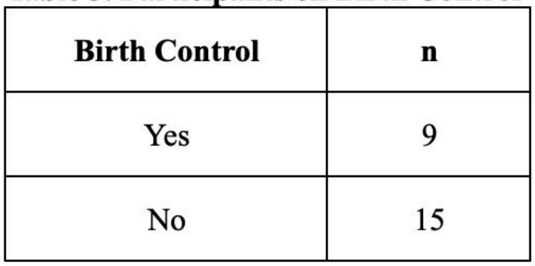


Table 2. Menstrual Cycle Phases of Participants with a Natural Cycle

Menstrual Phase	**n**
Menstruation	3
Follicular	9
Luteal	0

n=number

Table 3. Participants on Birth Control



Birth Control	n
Yes	9
No	15

n=number

The first maximal test's time ranged from 16 minutes and 8 seconds to 11 minutes and 39 seconds (mean 14 minutes and 7 seconds, SD 1 minute 14 seconds). The second maximal test's time ranged from 16 minutes and 16 seconds to 12 minutes (mean 13 minutes and 51 seconds, SD 1 minute 18 seconds). Out of 48 VO_2 max tests, 44 met the criteria for a true maximal test. The average VO_{2max} was 45.40 ml/kg/min with the maximum being 62.9 ml/kg/min and the minimum VO_2 being 34.9ml/min/kg. Mean values for maximal heart rate and average heart are shown in Table 4.

Table 4. Mean Heart Rate Values and Coefficient of Variation for Each Stage

	Mean Max HR T1	Std Dev Max T1	Mean Max HR T2	Std Dev Max T2	CV% Max HR	Mean Avg HR T1	Std Dev Avg T1	Mean Avg HR T2	Std Dev Avg HR T2	CV % Avg HR
Rest										
Catapult	73.6	9.0	75.9	9.9	14.7%	69.2	8.4	70.7	7.9	12.8%
EKG	81.3	7.6	81.6	7.0	10.4%	68.7	7.3	71.0	7.8	11.2%
Stage 1										
Catapult	103.0	8.8	102.7	7.9	7.6%	98.0	8.2	99.5	7.8	7.9
EKG	109.3	10.2	110.1	9.5	9.1%	102.4	11.4	103.5	10.9	10.4%
Stage 2										
Catapult	140.6	28.0	139.1	29.8	22.4%	133.1	27.0	134.4	30.4	23.1%
EKG	165.7	8.6	165.0	9.2	6.2%	159.6	8.4	158.5	8.4	5.7%
Stage 3										
Catapult	158.3	22.7	160.0	22.0	14.1%	151.2	26.1	154.6	23.3	16.1%
EKG	185.6	5.7	185.3	5.6	3.0%	177.7	7.8	177.3	8.0	4.3%

*HR=heart rate, Std Dev=standard deviation, Avg=average, CV=coefficient of variation

The reliability of the Catapult heart rate monitor was assessed during rest, stages one, two, and three using ICC. Catapult heart rate max measurements had moderate reliability during resting condition and stage one. Catapult heart rate max lost reliability as intensity increased. The Catapult average heart rate measurements displayed good reliability during resting conditions, and in stage one. Catapult average heart rate displayed and poor reliability in stages two and three (Table 5). The reliability of a single trial can also be seen in Table 6?. Catapult max heart rate for a single trial displayed poor reliability for every single stage. Catapult average heart rate displayed moderate reliability during resting conditions and stage one. As intensity increased, reliability of a single trial decreased.

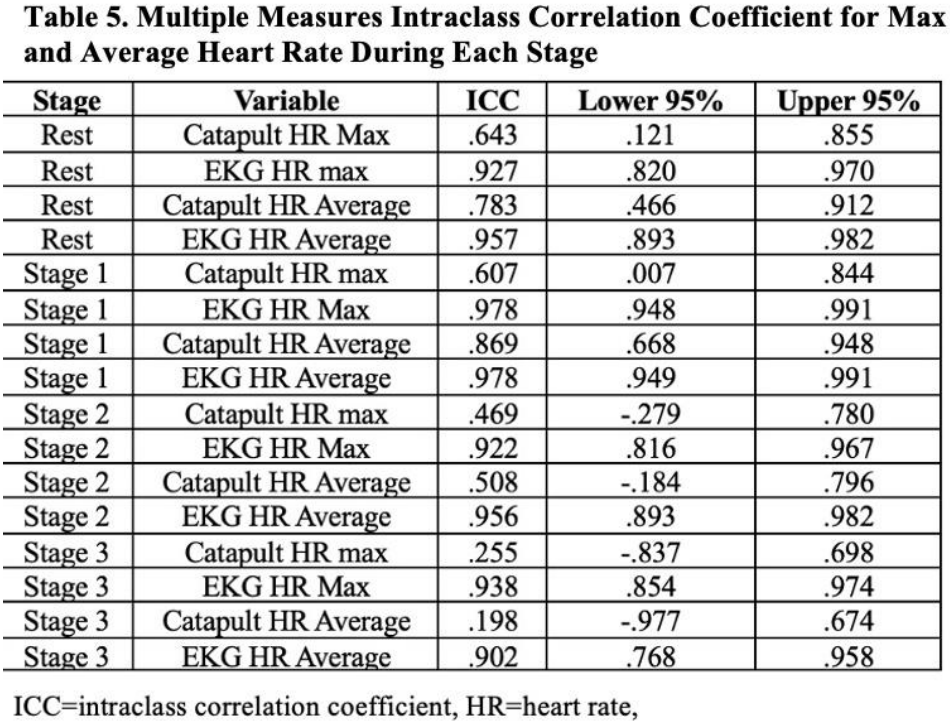


Table 5. Multiple Measures Intraclass Correlation Coefficient for Max and Average Heart Rate During Each Stage

Stage	Variable	ICC	Lower 95%	Upper 95%
Rest	Catapult HR Max	.643	.121	.855
Rest	EKG HR max	.927	.820	.970
Rest	Catapult HR Average	.783	.466	.912
Rest	EKG HR Average	.957	.893	.982
Stage 1	Catapult HR max	.607	.007	.844
Stage 1	EKG HR Max	.978	.948	.991
Stage 1	Catapult HR Average	.869	.668	.948
Stage 1	EKG HR Average	.978	.949	.991
Stage 2	Catapult HR max	.469	-.279	.780
Stage 2	EKG HR Max	.922	.816	.967
Stage 2	Catapult HR Average	.508	-.184	.796
Stage 2	EKG HR Average	.956	.893	.982
Stage 3	Catapult HR max	.255	-.837	.698
Stage 3	EKG HR Max	.938	.854	.974
Stage 3	Catapult HR Average	.198	-.977	.674
Stage 3	EKG HR Average	.902	.768	.958

ICC=intraclass correlation coefficient, HR=heart rate,

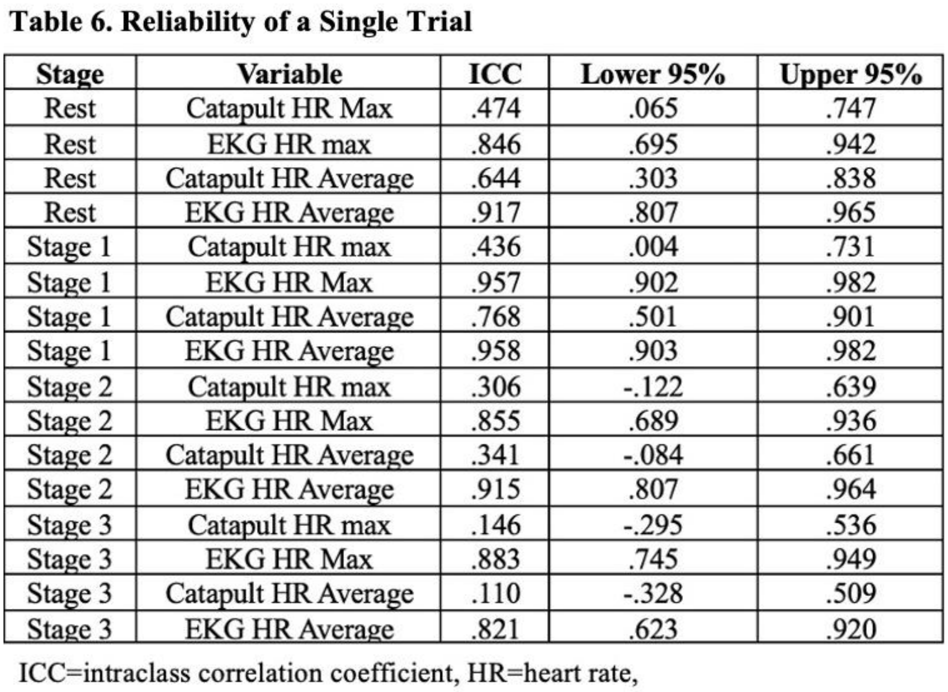


Table 6. Reliability of a Single Trial

Stage	Variable	ICC	Lower 95%	Upper 95%
Rest	Catapult HR Max	.474	.065	.747
Rest	EKG HR max	.846	.695	.942
Rest	Catapult HR Average	.644	.303	.838
Rest	EKG HR Average	.917	.807	.965
Stage 1	Catapult HR max	.436	.004	.731
Stage 1	EKG HR Max	.957	.902	.982
Stage 1	Catapult HR Average	.768	.501	.901
Stage 1	EKG HR Average	.958	.903	.982
Stage 2	Catapult HR max	.306	-.122	.639
Stage 2	EKG HR Max	.855	.689	.936
Stage 2	Catapult HR Average	.341	-.084	.661
Stage 2	EKG HR Average	.915	.807	.964
Stage 3	Catapult HR max	.146	-.295	.536
Stage 3	EKG HR Max	.883	.745	.949
Stage 3	Catapult HR Average	.110	-.328	.509
Stage 3	EKG HR Average	.821	.623	.920

ICC=intraclass correlation coefficient, HR=heart rate,

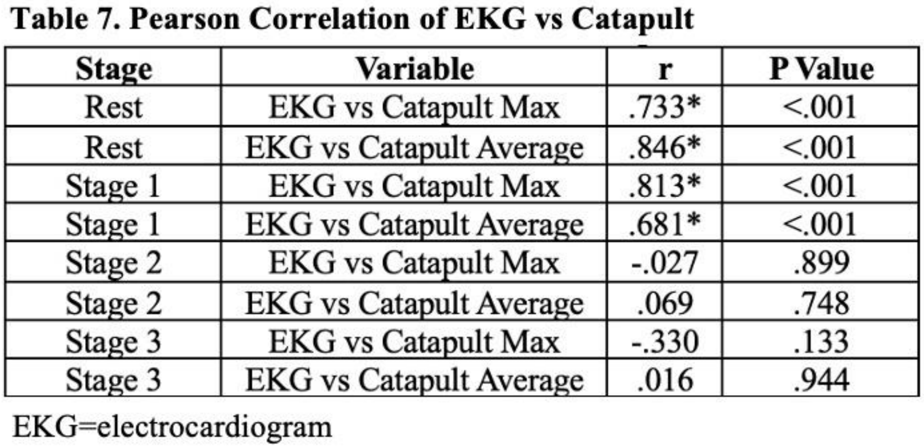


Table 7. Pearson Correlation of EKG vs Catapult

Stage	Variable	r	P Value
Rest	EKG vs Catapult Max	.733*	<.001
Rest	EKG vs Catapult Average	.846*	<.001
Stage 1	EKG vs Catapult Max	.813*	<.001
Stage 1	EKG vs Catapult Average	.681*	<.001
Stage 2	EKG vs Catapult Max	-.027	.899
Stage 2	EKG vs Catapult Average	.069	.748
Stage 3	EKG vs Catapult Max	-.330	.133
Stage 3	EKG vs Catapult Average	.016	.944

EKG=electrocardiogram

The Pearson correlations during resting conditions and stage one were greater than 0.60 (Table 7). As intensity increased Pearson correlation between the EKG and Catapult values decreased. All the values in stages two and three were less than 0.60. and were not statistically significant. Overall, the Catapult heart rate measurements displayed good accuracy during resting conditions and stage one but lost accuracy as intensity increased.

During resting conditions, coefficient of variation (CV) for Catapult's max and average heart rate were greater than 10%, displaying poor accuracy (Table 4). The CV during stage one (walking 3.1 mph) was less than 10% (7.60%) for Catapult's max heart rate and (7.90%) for average heart rate. As intensity increased, the accuracy of the Catapult measurements decreased. Poor accuracy was displayed during stage two for Catapult max (22.40%) and average heart rate (23.10%). The CV for Catapult's max (14.10%) and average heart rate (16.10%) displayed poor accuracy, and the EKG displayed acceptable levels of accuracy during stage three. Overall, the Catapult displayed poor levels of accuracy during all but the resting conditions.

Bland Altman analysis of resting max heart rate displayed a bias of -7.33 with most of the data points within the 95% limits of agreement (Figure 1).

Figure 1. Max HR During Rest

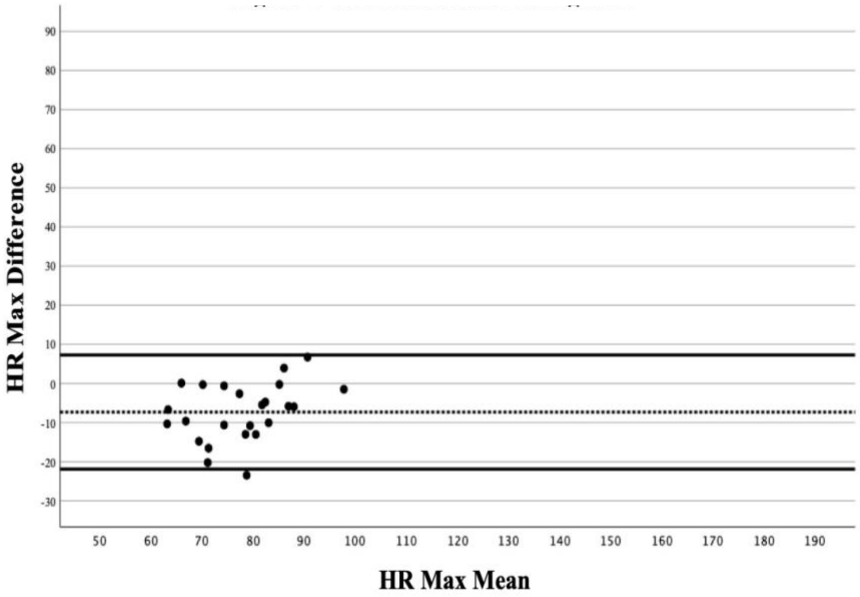


Figure 1. Bias= -7.33, SD= 7.43, Upper= 7.23,
Lower= -21.90

Bland Altman analysis of resting average heart rate displayed minimal bias of -0.41 with the data points evenly dispersed closely to the mean (Figure 2). Overall, the average resting heart rate collected by the Catapult heart rate monitor displayed a stronger accuracy than the max heartrate measurements.

Figure 2. Average HR During Rest

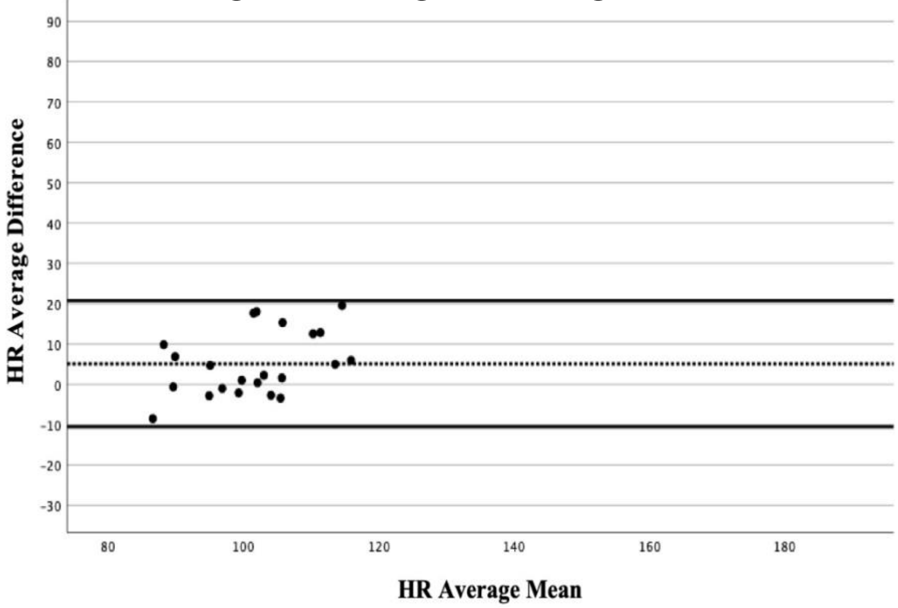


Figure 2. Bias= -0.40, SD= 4.68,

Upper= 8.76, Lower= -9.58

Bland Altman analysis of stage one max heart rate displayed a bias of 6.91 and data points were within the 95% limits of agreement (Figure 3). Bland Altman analysis of stage one average heart rate displayed a bias of 5.12 and the data points are scattered farther from the mean (Figure 4). The bias of the average heart rate is again less than the bias for max heart rate. This suggests that the average heart rate measurements during stage one are more accurate than the max heart rate measurements. Bland Altman analysis of stage two max heart rate displayed a large bias of 30.04 (Figure 5). The data points for stage two max heart rate are displaying a downward trend within the 95% limits of agreement. Bland Altman analysis of stage two average heart rate displayed a large bias of 30.44 with a downward trend (Figure 6). A downward trend suggests that the Catapult overestimates at lower heart rates and overestimate when heart rate increases. Bland Altman analysis of stage three max heart rate displayed a large bias of 25.35 (Figure 7). The data points for stage three max heart rate are displaying a

Figure 3. Max HR During Stage One

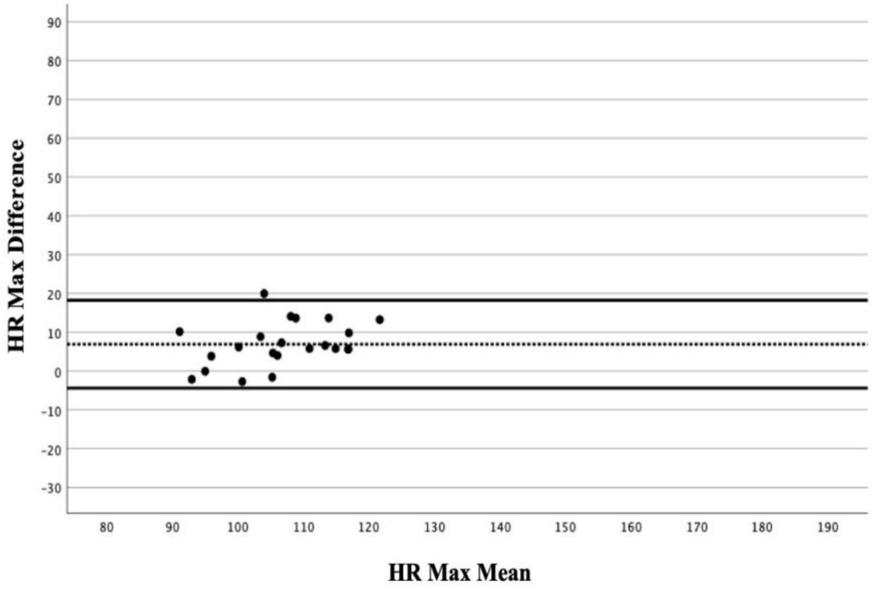


Figure 3. Bias= 6.91, SD= 5.77

Upper= 18.23, Lower= -4.40

Figure 4. Average HR During Stage One

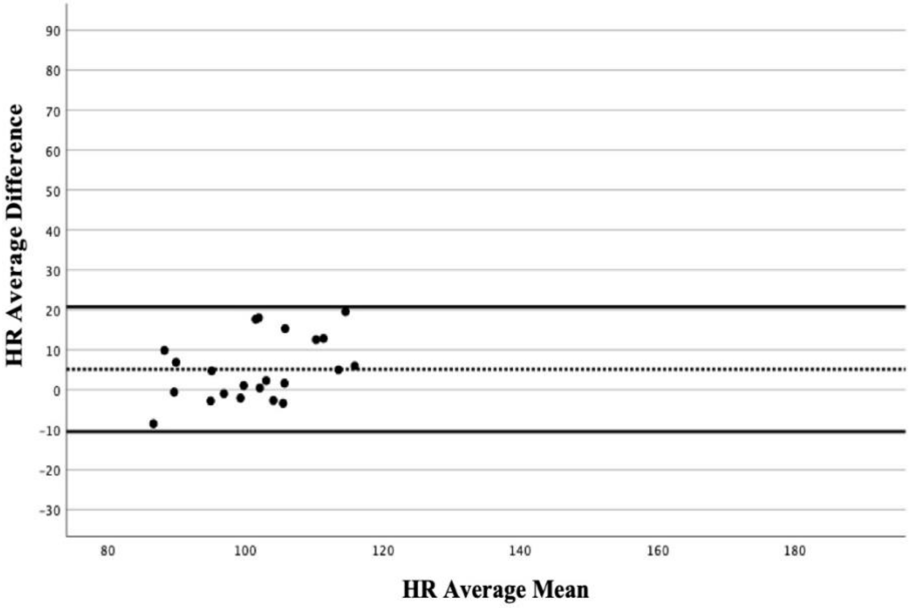


Figure 4. Bias=5.12, SD=7.97,

Upper=20.76, Lower= -10.51

downward trend within the 95% limits of agreement. Bland Altman analysis of stage one average heart rate displayed a large bias of 22.59 with a downward trend (Figure 8). The results suggest that Catapult loses accuracy as intensity increases. There was a large increase in the bias between stage one and stage two. Stage three also displayed a large bias. Figures 9-12 confirm that the EKG tracings for the criterion measure were appropriate.

Figure 5. Max HR During Stage Two

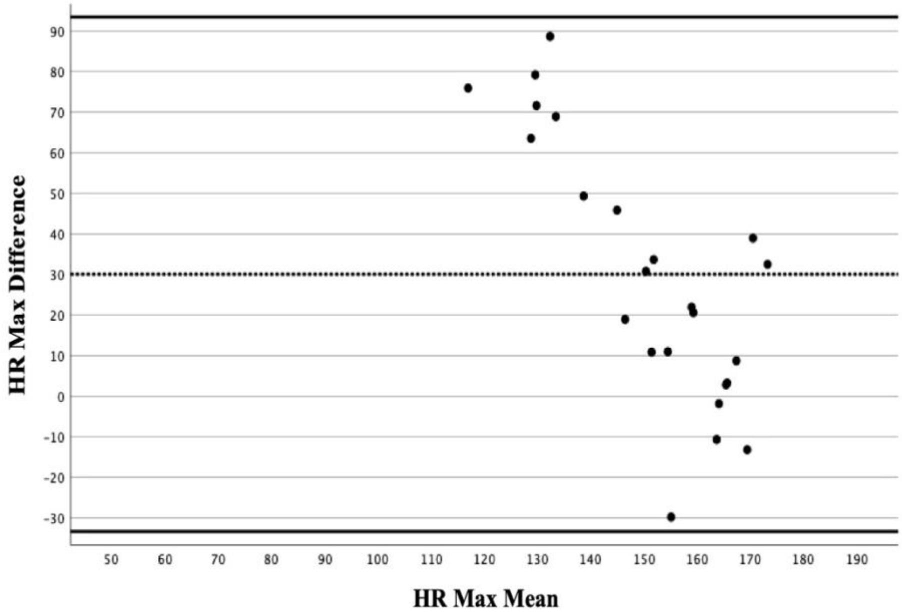


Figure 5. Bias=30.04, SD= 32.35,
Upper=93.46, Lower= -33.37

Figure 6. Average HR During Stage Two

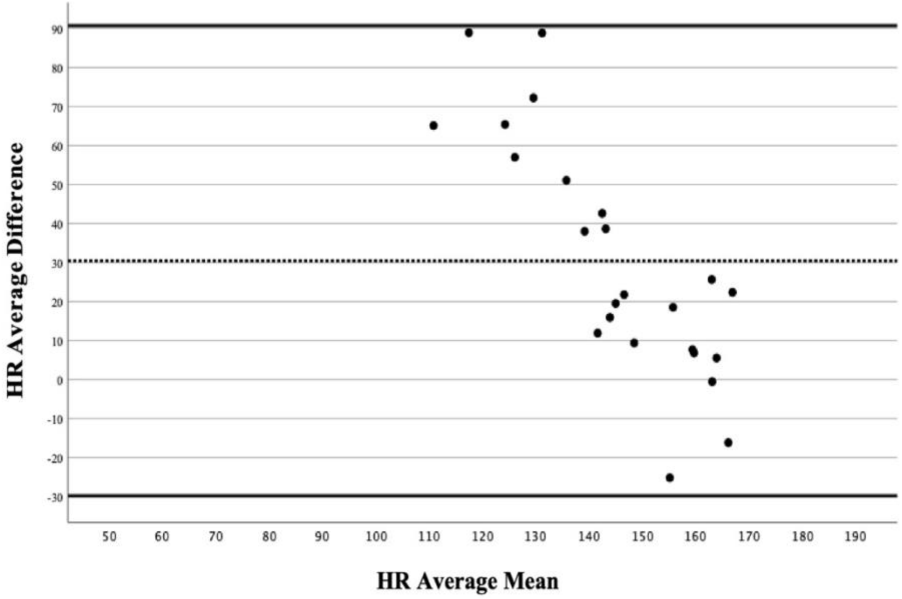


Figure 6. Bias=30.44, SD=30.75,

Upper=90.72, Lower= -29.83

Figure 7. Max HR During Stage Three

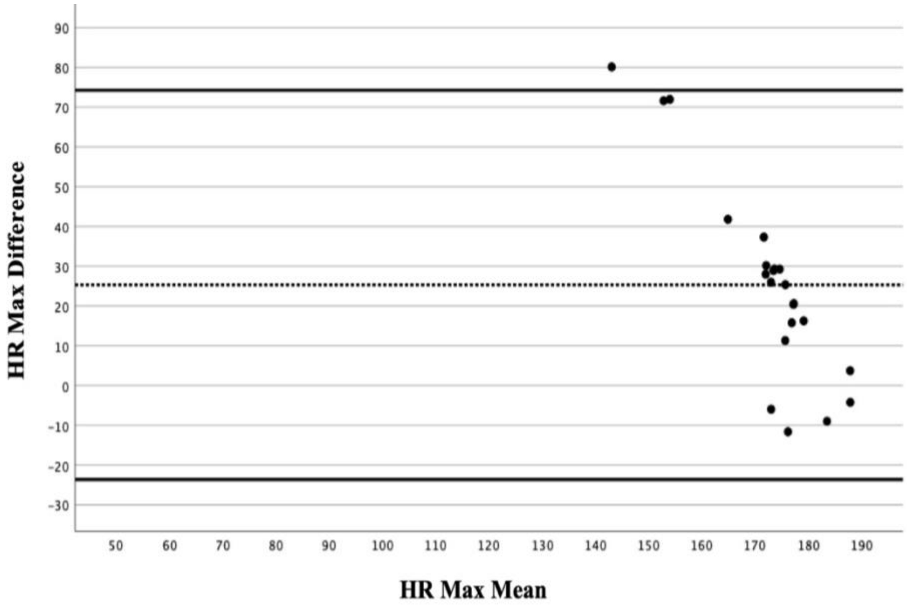


Figure 7. Bias=25.31, SD= 24.96,
Upper=74.24, Lower= -23.61

Figure 8. Average HR During Stage Three

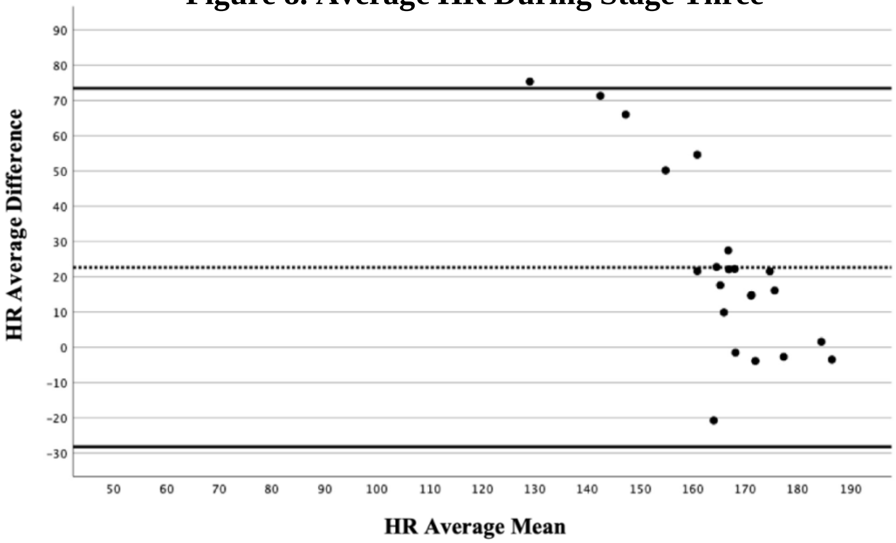


Figure 8. Bias=22.59, SD=25.93,

Upper=73.42, Lower= -28.23

DISCUSSION

The first aim of the study was to assess the reliability of the Catapult Sports' Vector Elite 2.1 heart rate monitor in female athletes at different exercise intensities. It was hypothesized that the Catapult Sports' Vector Elite 2.1 heart rate monitor would exhibit good intra-device reliability (ICC = at least 0.7) during rest, moderate and vigorous exercise intensities. The results of the study do not support this hypothesis. The secondary aim of the study was to assess the validity of the Catapult Sports' Vector Elite 2.1 heart rate monitor in female athletes at different exercise intensities. It was hypothesized that the Catapult Sports' Vector Elite 2.1 heart rate monitor measurements during rest, moderate and vigorous exercise would exhibit a Pearson Correlation of at least 0.7 when compared to a single-lead EKG. There would be minimal bias within 95% limits of agreement. Additionally, there would be an acceptable coefficient of variation of 5-10%. Again, the results of the study do not support the hypothesis. The results suggest that the heart rate monitor component does not provide an accurate measurement for average heart rate or max heart rate. The heart rate monitor also lacks reliability as intensity increases for these measurements as well. These findings challenge the usefulness of the heart rate monitor component for assessing heart rate in female athletes.

Reliability

It is a common theme among the literature that the reliability of commercially worn heart rate monitors decreases as exercise intensity increases regardless of the devices' location on the body (Khushhal et al., 2017), (Climstein et al., 2020). Across the board, most heart rate monitors are reliable during resting conditions such as sitting or lying down. Poor performance of vest and sports bra heart rate monitors during various exercise intensities has been documented (Navalta et al., 2020) (Haddad et al., 2020) (Parak et al., 2021). Navalta et al., evaluated three heart rate sports bras. Results displayed that the Adidas Smart Sports bra was not considered reliable for any of the testing conditions. The Berlei Sports bra met the minimum criterion for reliability. The Sensoria Fitness Biometric sports bra was the only heart rate monitor of the three that showed strong reliability during resting conditions but lost reliability as intensity increased.

Like heart rate sports bras, smart shirts that detect heart rate have also shown poor reliability (Haddad et al., 2020). Haddad et al., found that the Hexoskin wearable body metrics tool did an excellent job at measuring heart rate during pre-exercise conditions but proved to be unreliable during vigorous physical activity. When comparing a chest strap and a vest heart rate monitor, Parak et al., found that adjustable chest strap monitors are more reliable than vest heart rate monitors. Overall, the reliability of chest and vest heart rate monitors decreases as intensity of exercise increases.

Validity

In addition to reliability results, other studies display similar validity results to ours. The study conducted by Parak et al., suggested that a chest strap heart rate monitor displayed superior accuracy when compared to a vest heart rate monitor during various exercises. Overall, vest heart rate monitors lack reliability and validity as exercise intensity increases. A study conducted on the Armour39 chest strap heart rate monitor reported acceptable means for valid determination of heart rate (Flanagan et al., 2014). The authors reported the heart rate monitor is valid to measure heart rate in various bodily positions; however, their protocol provided minimal changes in body positions. Many researchers report that chest and vest heart rate monitors are valid during resting conditions and lose validity as intensity increases, like the current investigation. Parak et al., 2021, compared the validity of heart rate measures in three commercially available sports bras during walking and running. Out of the three smart sports bras that were analyzed, only one of the bras was valid during all three exercise stages. The researchers found that the Adidas Smart sports bra was valid only during rest. The Berlei sports bra was valid across multiple exercise intensities, and the Sensoria biometric bra was valid during rest and walking. Overall, there are very few heart rate monitor garments that are valid during various exercise intensities.

Potential Reasons for Inaccuracy and Unreliability

There are multiple potential reasons for the inaccuracy and unreliability of the heart rate monitor component of the Catapult Sports Vector Elite 2.1 garment. There were issues with sizing participants with garments, especially if they had larger or smaller chests. Because the garment sizing is fixed and cannot be adjusted to ensure full skin contact with the sensors that may be a potential reason for its' inaccuracy. Montes et al., noted that heart rate measurements of the Hexoskin smart shirt were impacted by the chest size of the individual. The limited sizing of sports bra heart rate monitor greatly impacts the garment's ability to accurately measure heart rate and provide the chest support the athlete requires (Navalta et al., 2020). Another potential reason for the Catapult's inaccuracy is the upper body movement involved during aerobic exercise. Increased bodily movement, particularly at the breast is a potential reason for inaccuracy of sports bras heart rate monitors (Navalta et al., 2020). The movement most likely causes mechanical artefacts causing the sensors to move against the skin. Elliot et al., also determined that increased torso movement during cycling increases the likelihood of the Hexoskin sensors moving around on the skin, in turn, increasing potential noise signals in the measurements. Overall, heart rate monitors embedded in sports bras or t-shirts tend to lack reliability and validity because of poor sizing, and increased torso movement during high intensity exercises.

VO_2max

According to ACSM guidelines, the average VO_2max of the participants (45.4ml/kg/min) is in the 85th percentile when compared to normal healthy people. However, when comparing the population to similar populations, there is a larger discrepancy. According to the literature, VO_2 max scores vary depending on the position of the individual for soccer players (Xing et al., 2023). Ingrbrigsten et al., 2011 tested the VO_2max of division I female soccer players. According to the study, defenders have a VO2max of 51.85±5.05 ml/kg/min. Midfielders have a VO_2max of 55.36±5.65 ml/kg/min and attackers o 52.94±3.17 ml/kg/min. Lastly, goalkeepers have a VO_2max 50.70±4.96 ml/kg/min. For division I field hockey players, there is limited literature on the aerobic, positional demands of female field hockey players. According to Smith et al., the average VO_2 max for a division I, field hockey player is 55.77±4.70 ml/kg/min. Overall, the VO_2max results of the participants were lower than what is found in the literature. The lower VO_2max scores were not expected. A potential reason for the VO_2max scores being lower is the current training phase that the athletes are in. A study conducted by Miller et al., found significant differences in aerobic capacity during different seasons of training. The current study was conducted during the off season for both sports; therefore, the athletes were not in peak condition.

There are studies that suggest cardiorespiratory metrics do not significantly change across the phases of the menstrual cycle (Ekberg et al., 2023) (Rael et al., 2021) (Williams et al., 2023). The aims of the study do not include investigating the impact of the menstrual cycle on VO_2max. Therefore, we cannot elucidate if the menstrual cycle phases influenced the aerobic capacity of participants.

Strengths and Limitations

The utilization of a sport specific protocol can be considered a strength of this study. Another strength is ensuring reliability of the testing sessions by scheduling within the same phase of the participant’s menstrual cycle. The speeds chosen for the protocol stem from GPS data of division I female field hockey players. There are a few limitations to this study as well. The participants of the study were predominantly Caucasian females. Therefore, our results are not applicable to all ethnicities and both sexes. Even though the protocol was designed for division I female field hockey players, this may also be a limitation to the study as well. The speeds for the protocol are not applicable for normal population or other sports. Another limitation of this study is the display methods of both measurements. The EKG displays individual heart beats in form of R-R intervals during data collection, and Catapult does not. When outliers measured by the EKG were identified, they were further analyzed. Heart beats detected by the EKG that were considered outliers were removed from the 1-minute section utilized for analysis. Outliers of the Catapult measurements for the entire minute were removed from analysis because the software does not provide the opportunity to view individual heartbeat intervals. Therefore, with Catapult, researchers are not capable of excluding individual heart beats.

Future research

Future research should explore the reliability and accuracy of the device in more diverse populations. This study utilized female participants; therefore, future research should explore the accuracy in males. Future research should also explore the accuracy and reliability of the device with other protocols that are specific to other sports. Other races/ethnicities?

CONCLUSION

In conclusion, the Catapult Sports Vector Elite 2.1 heart rate monitor component is not accurate when compared to a single lead EKG. In addition to its inaccuracy, the heart rate monitor component is only reliable during resting conditions. The heart rate monitor component loses reliability as the intensity of aerobic exercise increases. Overall, the device is not reliable, therefore the heart rate monitor cannot be valid. The findings of this study are similar to current literature on sports bra and vest heart rate monitors.

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