Metabolic and Physiological Differences Between Knee Crutch Ambulation and Normal Gait: A Case Study

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Abstract

The knee crutch was originally developed in 1999 by the company iWalkFree as an assistive aid for individuals with below-the-knee injuries (iWALKFree). Although it has been over 20 years since the knee crutch was first commercialized, there have been very few studies published on how it affects the user. In addition, most studies concerning the knee crutch only describe the biomechanical and EMG data, instead of physiological and metabolic data. This two-participant case study research employed a portable gas analysis instrument to understand the minute ventilation (VE), oxygen (O_2) consumption, and heart rate differences between walking with a knee crutch and walking with no assistive device. Upon comparing the results of this study to previous research, it was determined that the knee crutch allows greater efficiency than using other assistive devices such as traditional crutches and the knee scooter, indicated by lesser metabolic and physiologic stress.

Introduction

Nearly 2 million ankle sprains are reported annually within the United States, with a range averaging between two and seven ankle sprains per every 1000 citizens (Herzog et al., 2019). Acute ankle injuries compose 15% of all injuries reported amongst college athletes in the United States, and 15-17% reported in high school athletes (Herzog et al., 2019). Due to the ranging severity, not everyone who acquires acute ankle injury brings themself into the emergency room or doctor's office. Because of this, the numbers provided by studies concerning ankle sprain epidemiology are likely an underestimation of the real values. The severity of ankle sprains often varies, with some necessitating minimal recovery time, while 60% cause long-term disability that interferes with an individual's career and lifestyle (Waterman et al., 2010).

Many individuals who sustain a foot or ankle injury are often placed under non-weight bearing restrictions, meaning an assistive device is necessary to help the person remain mobile during their recovery period. Traditional crutches, also referred to as axillary crutches, are the most common option when an individual is looking for a non-weight bearing assistive device (Odebiyi, 2020). This type of assistive device features metal shafts that extend upwards from the ground to a cushioned pad that is secured under the armpit during ambulation (MacGillivray, 2016). The traditional crutch features a swing-through gait in which the user keeps their injured leg above the ground at all times and uses their non-injured leg and both shafts of the crutches to move around (MacGillivray, 2016).

Despite the immense popularity of traditional crutches and knee scooters amongst those who have lower-limb, non-weight bearing injuries, these devices may not be the most efficient or versatile options. Traditional crutches come with the challenge of utilizing and fully relying on the upper extremities to enable ambulation. If an individual has limited upper body strength or also has an upper extremity injury, traditional crutches are not a viable option. In addition, using traditional crutches comes with its own risks of bilateral radial nerve compression, otherwise known as crutch palsy (Rambani, 2007). This can occur when an individual is not properly taught how to use crutches, or upon onset of fatigue and applies too much pressure through their underarm area when ambulating (Rambani, 2007). The knee scooter comes with its own stipulations, including usage of the upper extremities. Furthermore, individuals who use knee scooters cannot use stairs because of the wheels. One potential concern with using the knee scooter is cases of deep-vein thrombosis, resulting from fixed knee flexion of the injured leg during ambulation (Davidson et al., 2022). However, a retrospective study published in 2022 found that only .8% of participants reported deep vein thrombosis as a direct result of scooter usage (Davidson et al., 2022). Due to the similarities in fixed knee flexion, it is likely that this value would be similar in a study concerning deep vein thrombosis in knee crutch users.

Although traditional underarm crutches have been around for centuries, the knee crutch has only been around several decades (iWALKFree). The knee crutch, also known as the hands-free crutch, is an assistive device that holds the injured leg in knee flexion at 90 degrees (iWALKFree). The lower leg is supported by a pad spanning the length of the shin (iWALKFree). Where the pad meets the knee, it is attached to two metal rods that both extend up the leg and to the floor for support (iWALKFree). On the floor, the metal rods attach to a wide base to help the user maintain balance (iWALKFree). The metal rods going up the leg attach to a strap that goes in front of the lower thigh and a strap that goes around the upper thigh to secure the device to the individual (iWALKFree). After the knee crutch design was approved in 1999, the Canadian company iWALKFree began publicly selling the first commercial knee crutch in 2000 (iWALKFree). Since then, iWalkFree has developed a second edition, while other companies such as Freedom Leg have replicated the design and added their own modifications (iWALKFree).

The purpose of this knee crutch study is to give a baseline understanding of the physiological and metabolic differences between walking with and without a knee crutch. Researchers will be able to build upon the results of this study by recruiting a larger student population, and conducting a similar study. This will increase the generalizability of the findings, making the study more meaningful in the world of research. New knowledge in using the K4 b^2 technology will enhance future physiologic and metabolic research conducted at Oakland University, and allow such studies to become more efficient in data collection and interpretation.

Current Research

Due to the relatively new technology of the knee crutch, there have only been a limited number of studies conducted regarding it, each with their own parameters and limitations. One such article compared joint motion and reaction force among individuals using the knee crutch, standard crutches, and gait without aid (Orishimo, 2021). In the study, Orishimo and his team of researchers used force plates and nearly a dozen cameras to analyze the gait of the participants as they walked five meters (2021). The results showed that individuals using the knee crutch walked 33% slower than traditional crutch users, and 44% slower than those with no aid (Orishimo, 2021). Additionally, they observed the knee crutch group generated more force from within their low back than the other groups, but generated less reaction force from their hip than the traditional crutch group (Orishimo, 2021). This biomechanical data is beneficial to understanding where the patients will be experiencing more wear and tear on their bodies when using the knee crutch. However, the data from this study did not include the patient's physiological and metabolic responses when using the knee crutch. These are important data to keep in mind because they represent the patient's respiratory exertion and can affect perceived effort of using this assistive device, thus making the device more or less desirable to other patients.

In 2020, a study was conducted concerning the electromyographic (EMG) effects of using a knee crutch compared to using traditional underarm crutches (Dewar & Martin). In this study, EMG sensors were placed on the participant's non-weight bearing leg on the rectus femoris, gastrocnemius, gluteus maximus and vastus lateralis (Dewar & Martin, 2020). Each participant started the first trial with the knee crutch before resting five minutes and transitioning to the traditional crutches for the second trial (Dewar & Martin, 2020). For each trial, the participant's sensors were analyzed for a period of 15 seconds during a self-paced, leisurely walk down a 30 meter walkway (Dewar & Martin, 2020). Every EMG sensor, besides the vastus lateralis sensor, recorded a significantly higher rate of activity when using the knee crutch (Dewar & Martin, 2020). This is crucial because it shows that when using the knee crutch, the individual may have less risk of muscle atrophy compared to using traditional crutches, as the non-weight bearing leg plays a significantly larger role in ambulation.

In 2021, Dewar and Martin added more researchers to their group and compared the EMG effects of using a knee crutch and knee scooter (Dewar et al., 2021). The researchers noticed the same muscles showed a significant increase in electrical activation and usage as demonstrated in the previous 2020 study when compared to the knee scooter (Dewar et al., 2021; Dewar & Martin, 2020). The researchers did note, however, that patients preferred the knee scooter slightly more than the knee crutch (Dewar et al., 2021). In both studies, the researchers suggested the data collected may help doctors understand which mobility aid will result in less muscle atrophy, which is a major concern when a patient is placed under weight-bearing restrictions (Dewar et al., 2021; Dewar & Martin, 2020). To add onto the EMG data collected within these studies, it is crucial to research and understand the physiological and metabolic aspects of using such devices. EMG data can be directly applicable to how an individual muscle is contracting via innervation, but the physiological and metabolic aspects have a broader application as they encompass the whole body's exertion.

Not only is it important to note the activation occurring within the muscles of the support leg while using each assistive device, but it is also important to understand the impact the support leg is sustaining while using each device. In a study conducted at Lakeland University, researchers found that the support leg had the highest peak ground reaction forces when using the traditional crutches, and the lowest peak ground reaction forces when using the knee scooter (Lange et al., 2019). The higher forces found in the traditional crutches may cause the support leg to be at danger for potential overuse injuries (Lange et al., 2019). The lower forces discovered in the knee scooter trial may indicate an underutilization of the support leg, raising the possibility for muscle atrophy and loss of strength (Lange et al., 2019).

Other types of lower extremity injuries, especially pertaining to the knee joint, may have immobilization protocols rather than weight restrictions. These injuries may necessitate a knee-ankle-foot orthoses (KAFO), which fully restricts knee flexion, or a dynamic knee brace system (DKBS), which limits knee flexion, to assist in rehabilitation. Several studies have been conducted regarding such devices and the differences in oxygen (O_2) consumption. A case study was conducted with a healthy, injury-free participant, who was given time prior to the day of testing to gain experience ambulating with each type of brace. When compared to walking without an assistive device, the results showed that while the participant was wearing the DKBS, a 20%-30% increase in O_2 consumption was observed, and while the participant was wearing the KAFO, a 50%-100% increase in O_2 consumption (Irby, 1999). In a study conducted by the University of Minnesota, participants consisted of males who refused to have surgery following an ACL injury (Zetterlund, 1986). Each performed a treadmill running test both with and without the Lenox Hill Derotation brace, offering results that showed a significant 4.58% increase in O_2 consumption while wearing the brace (Zetterlund, 1986).

The current research will attempt to address the main gap in knee crutch research, which is a lack of knowledge surrounding the physiological and metabolic impact of using a knee crutch. As shown by the current research available, there have been very few published studies that discuss the knee crutch, let alone the O_2 consumption and heart rate data of individuals using this assistive device. Understanding O_2 consumption and heart rate determines the energy expenditure of the aerobic system, which is the energy system utilized during ambulation (Silva, 2021). This study will be investigating O_2 consumption and heart rate of individuals as they walk along a predesignated path both with and without the knee-crutch, allowing the researchers to compare the findings. As a result of this study, medical professionals will be able to compare the energy expenditures of different assistive aids, including the knee crutch, to determine which is closest to the energy expenditure of unassisted walking. Thus, studying the physiological and metabolic effects will allow doctors to successfully recommend the best assistive device for their patients to promote and not hinder them on their road to recovery. The data collected from this research will allow physical therapists to have more insight when working with patients who are using the knee crutch, and will allow more specific care to be taken when catering to a patient's specific rehabilitation needs.

Methodology

This case study involved two participants: one male and one female, both 20 years old. The individuals were generally healthy, and able to walk successfully without any assistive aid. One week prior to the day of testing, the researchers led the participants through a series of balance tests, utilizing the Balance Tracking System. These balance tests were used as a screening tool to ensure the participants did not have a high fall risk before participating in the study. Should any participants in future knee crutch studies have high fall risk, they should be excluded from the study. After baseline balance data was collected and showed the participants had a low fall risk, the participants were strapped into the knee crutch and led through the same test. Both participants showed lesser balance with the knee crutch, but were still both at a low fall risk. The participants were then able to practice ambulating with the knee crutch by taking several laps around the laboratory. A researcher walked alongside the participant to ensure the participant's safety. Practicing with the knee crutch before the day of data collection was deemed necessary so the results more accurately reflect physiological and metabolic cost of using this assistive device. Additionally, practicing with the knee crutch allows the study results to be more generalizable to individuals who utilize this assistive device for a longer period of time as they heal from their injury. The researchers also took this day to become more familiar with data collection and how to read the data collected by the K4 b^2.

A portable metabolic device known as a K4 b^2 and a heart rate monitor was employed in this study to determine the O_2 consumption and heart rate of the individuals being tested. First, the K4 b^2 was assembled. Next, the instrument was calibrated. More information on equipment assembly and calibration can be found in Appendix A.

Once calibration was complete, the K4 b^2 mask was placed securely over the participant's nose and mouth via six velcro straps to ensure the participant only breathed through the turbine. The participant was instructed to forcefully exhale to determine no air was escaping from around the edges of the mask. A polar heart rate monitor belt was wrapped and secured around the lower part of the participant's chest, in contact with the skin. The K4 b^2 unit was attached to the front of the chest via harness, and the battery pack was attached to the same harness but situated on the back of the individual. The heart rate probe that received the signal from the heart rate belt was connected to the K4 b^2, and the receiving box was clipped onto the harness. The harness was tightened until the K4 b^2 was not at risk for moving around while the participant walked, but not so tight as to restrict movement. Figure 1 depicts the set-up of the equipment and knee crutch on a participant.

Figure 1: Participant with knee crutch and K4 b^2 set-up

Once the participant was set up, the researcher waited until the breathing and heart rate of the participant leveled out. The researchers started the recording process on the K4 b^2 to gather baseline measures of inspired O_2 and heart rate while the participant was standing still. After these initial measures had been taken, the participant was instructed to walk along a predetermined path within the Human Health Building at a comfortable walking pace. The first day of testing consisted of a five-minute walk with an unassisted, normal gait at a self-selected pace. The five-minute time frame for each trial was selected as a means of getting each participant to a point of steady-state exercise, a state that typically occurs after 3 minutes of continuous exercise (McArdle et al., 2015, p. 163). This steady-state is observable by a plateau in oxygen consumption values (McArdle et al., 2015, p. 164). Allowing participants to self-select an appropriate pace allows for maximization of gait efficiency, and a better reflection of daily life (Moran et al., 2014). After the first participant had completed their five minutes of walking, the equipment was completely taken off of the participant. The turbine and end cap for the mask was sanitized with a high-grade, fast acting disinfectant solution, only requiring five seconds of exposure. The turbine and end cap were then rinsed thoroughly because of their corrosive properties when in contact with skin. The rest of the equipment was extensively cleaned with a disinfectant wipe. Once the equipment was clean and dry, the next participant was assembled. Between same-day trials, the K4 b^2 did not need to be recalibrated. The second participant was set up in the same manner as the first, and participated in the same five-minute trial.

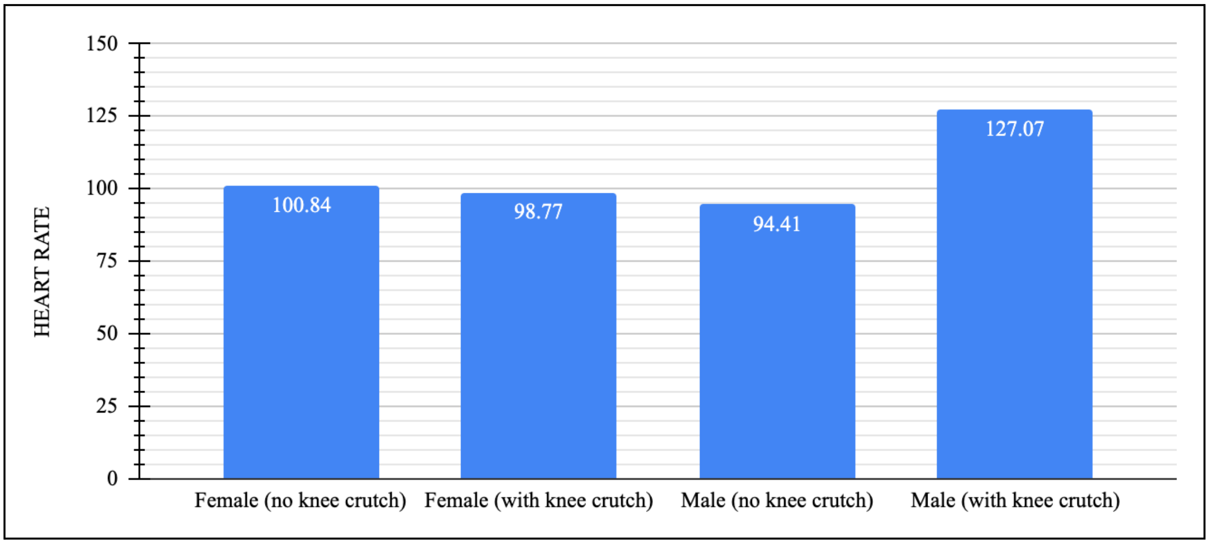
A week later, the second day of testing took place. On this day of testing, the same set-up process was utilized, including equipment calibration and participant preparation. The participant ambulated with the knee crutch for five minutes along the same path as the first testing day at a self-selected pace. After the first participant had completed their five minutes of walking, the equipment was completely taken off of the participant, and disinfected in the same manner as the first day of testing. Once both testing days were completed, the participants were thanked for their time, and the collected data was analyzed by the researchers.

Each lap completed by the participant was 83 meters in length. To determine average speed of each trial, the amount of laps completed, rounded to the nearest quarter lap, was multiplied by 83 to determine the total distance covered. This distance was then divided by five to determine the average speed in meters per minute (m/min). To calculate percent differences in speed between trials, the average speed achieved with the knee crutch was divided by the average speed achieved while walking without the knee crutch. To determine the percent difference between heart rate data over the last minute of exercise from either participant, average knee crutch values were divided by average normal gait walking values.

Results

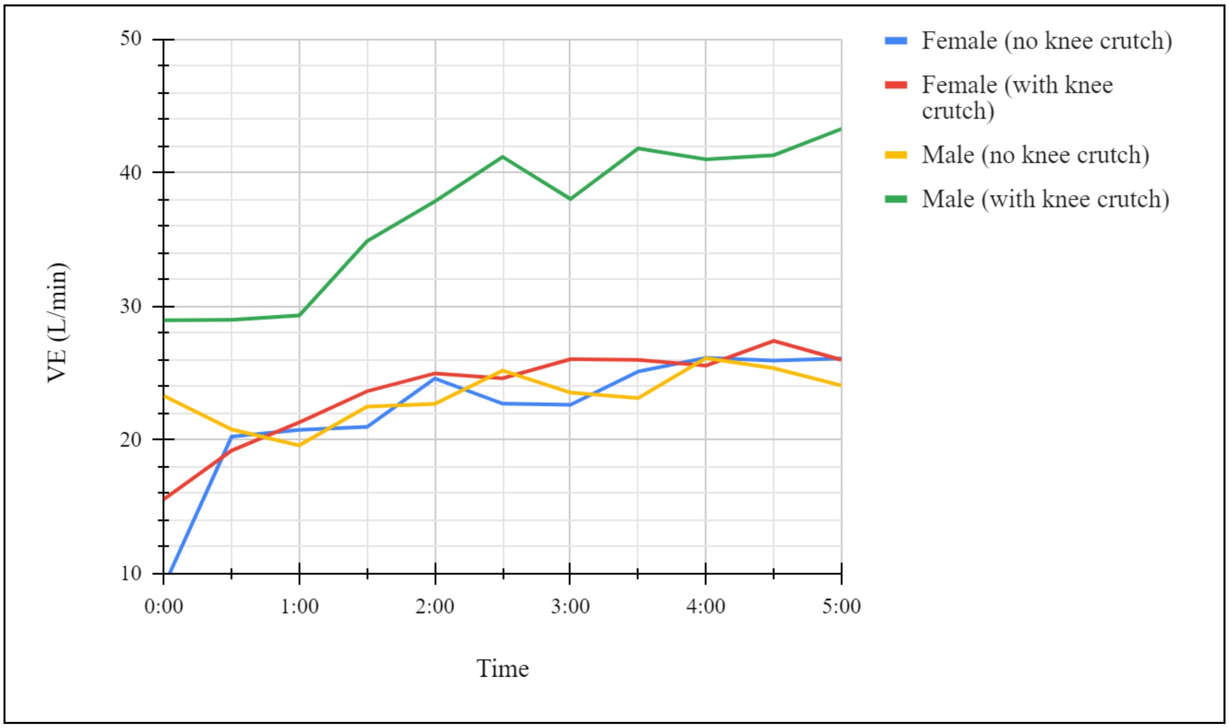
For the trials without the knee crutch, the female's average speed was 103.75 m/min and the male's average speed was 91.3 m/min. For the trials with the knee crutch, the female's average speed was 49.8 m/min and the male's average speed was 62.25 m/min. The average heart rate throughout the last minute of each trial is displayed below in Figure 2. Between the trial with and without a knee crutch, the results showed a 2.05% decrease in heart rate over the last minute of exercise for the female participant, and a 34.59% increase for the male participant.

Figure 2: Average heart rate over the last minute of walking



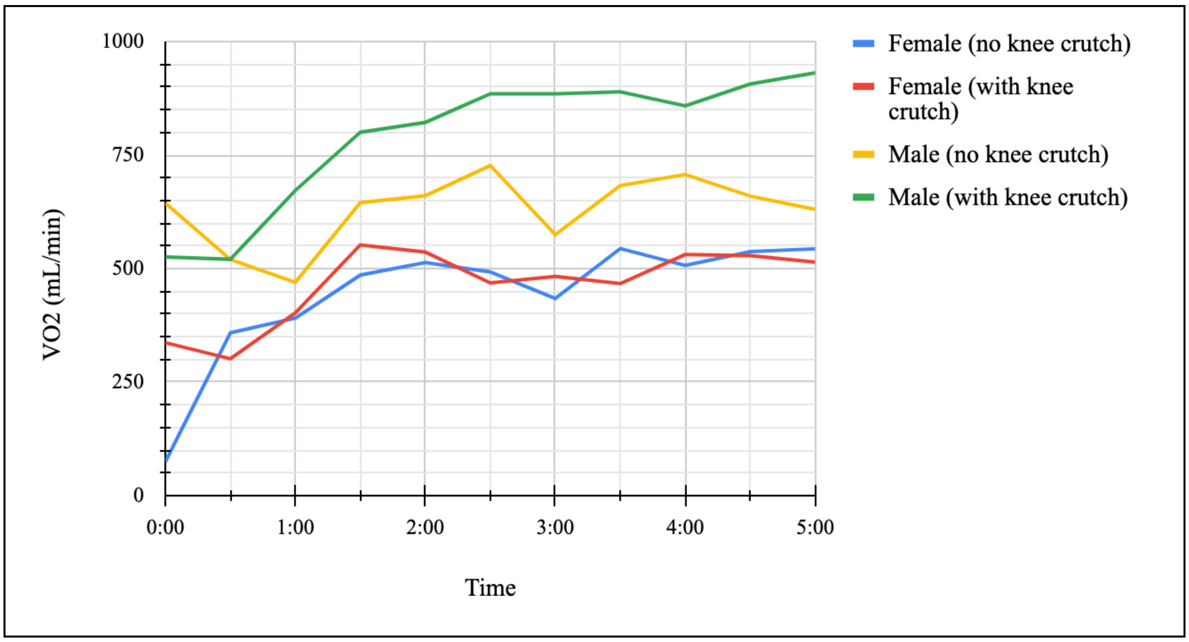
Minute ventilation (VE) is the volume of air that enters the lungs via inspiration every minute. Figure 3 demonstrates the starting value of VE, along with 30 second averages of VE across the five-minute ambulation trials. When analyzing the VE of both participants throughout the five-minute test, a sharp increase is evident when exercise first began, and as exercise continued, the rate of minute ventilation plateaued.

Figure 3: VE values averaged every 30 seconds over five minutes of walking



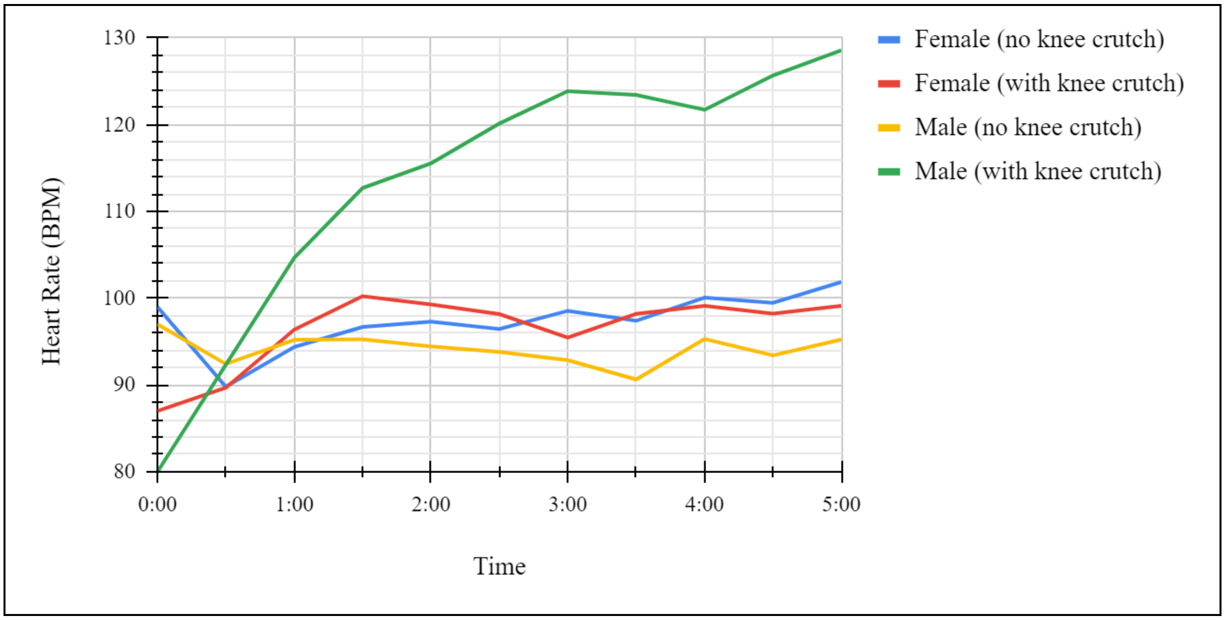
VO_2 is a measure of the volume of O_2 utilized during exercise. These values are displayed in Figure 4, which includes the initial values for each trial, along with 30 second averages of VO_2 across the trials. There is a steady increase in VO_2 in three of the five-minute trials, but a sharper initial increase is seen in the trial with the male participant wearing the knee crutch.

Figure 4: VO_2 values averaged every 30 seconds over five minutes of walking



Heart rate data recorded throughout the tests are displayed in Figure 5, including the initial values and 30 second averages across the tests. There is not a notable increase in heart rate between resting and ambulation values, except for the trial with the male wearing the knee crutch.

Figure 5: Heart rate values averaged every 30 seconds over five minutes of walking



Discussion

The female did not have a noticeable difference between trials wearing or not wearing the knee crutch, showing overlaps in data between both trials. This is potentially because the participant walked rather quickly during the trial without wearing the knee crutch, likely a subconscious result of being observed while walking. The participant then likely attempted to maintain a similar exertion and intensity for the trial while ambulating with the knee crutch, which would account for the similarities between trials. Based on Figure 3, 4, and 5, it is evident that male knee crutch trial produced prominently higher values than the other trials. This is likely because the male walked slower than the female in the trial without wearing the knee crutch, but walked faster than the female for the trial wearing the knee crutch. While wearing the knee crutch, the female participant walked at 48% of her speed walking without the knee crutch, and the male participant walked at 68% of his speed walking without the knee crutch. This shows that the male was likely trying to walk as quickly as possible for the trial wearing the knee crutch, or that the female was having trouble navigating while wearing the knee crutch.

The values collected from this study can be compared to previous research concerning the knee crutch and other assistive devices to derive similarities and differences. In one study conducted in 1990, researchers studied use of traditional crutches and Sure-Gait crutches (Annesley et al., 1990). Sure-Gait crutches are very similar to traditional crutches, except they have a rounded base, compared to the peg base of traditional crutches. The participants in this study ambulated for five minutes on a treadmill without an assistive device, and with both types of crutches (Annesley et al., 1990). After the second minute, a 2% grade was added to increase heart rate, and lowered back to 0% when this was achieved (Annesley et al., 1990). The results showed the values of VO_2 plateau starting around minute four, and reached as high as about 2.1 L/min at minute five for both types of crutches (Annesley et al., 1990). In this knee crutch study, the final 30 second average values recorded at five minutes were .514 L/min and .931 L/min in the female and male participants respectively for the trials conducted while wearing the knee crutch. Although this knee crutch study did not involve anything to intentionally raise the participant's heart rate, the same increase and plateau in VO_2 is evident, indicating that participants in both studies reached a steady state exercise VO_2 level. When looking at the heart rate data gathered in the crutch study, another plateau is seen starting at around minute 4, with ending values of 140 BPM for both Sure-Gait and traditional crutches (Annesley et al., 1990). This can be compared to the final averages of 99.1 BPM and 128.6 BPM for female and male participants respectively for the trials conducted while wearing the knee crutch. When comparing the two studies, it is evident that ambulation with crutches is more taxing on the metabolic and physiological systems of the body than when using the knee crutch. The main difference between studies however, is that in the present knee crutch study, participants were enabled to choose their own walking speed, while a set walking speed of 1.5 miles per hour (mph) was used in the crutch study (Annesley et al., 1990). This potentially makes gait less efficient, increasing the amount of work the participant's body had to perform.

Another study published in 2014 utilized elbow crutches, and recorded data of 31 participants ambulating with crutches on a level surface and ascending stairs (Moran, 2014). Elbow crutches are similar to traditional crutches, but mitigate the potential for axilla injury in that the user grips a short horizontal bar that is perpendicular to the shaft of the crutch, and the posterior forearm is supported by a cuff situated at the top of the crutch. This study also utilized the K4 b^2 and a self-selected walking pace, supporting the comparison of this study and the present knee crutch study. The average VO_2 values collected during the 30 meters of level surface elbow crutch walking was found to be 1.164 L/min for females and 1.150 L/min for males (Moran, 2014). Although these values are roughly double what was recorded for the female participant in the present knee crutch study, the male participant had a final average VO_2 of .931 L/min, which is only about 0.200 L/min lower than the elbow crutch study. The average heart rate among both genders during elbow crutch walking was 117.0 BPM, which can be compared to the values of 99.1 BPM and 128.6 BPM for female and male participants respectively for the trials conducted while wearing the knee crutch (Moran, 2014). The elbow crutch participants did not walk nearly as far as the knee crutch participants, potentially meaning that the values derived from the elbow crutch study might have been higher if the participants had to use the elbow crutches for five minutes. From these two studies, it can be assumed that the metabolic and physiological stress from elbow crutch walking is only slightly higher or comparable to using a knee crutch.

Another study focused on how the user's body showed signs of fatigue after walking for six minutes with the knee crutch and then with traditional underarm crutches (Martin et al., 2019). The results showed that the traditional crutch users were able to reach an average of 299 meters, while the knee crutch users were able to reach 272 meters. Despite this, the results showed that patients using the traditional crutches were nearly twice as out of breath as when they used the knee crutch (Martin et al., 2019). The significant difference between pre-activity and post-activity heart rate when using either device also substantiated that using the knee crutch was metabolically less challenging (Martin et al., 2019). The researchers surveyed their participants and found that 86% preferred the knee crutch over the alternative (Martin et al., 2019). When asked about discomfort in ambulation with each device, 68% reported the handles of the traditional crutches, and 7% reported the proximal leg strap in the knee crutch (Martin et al., 2019). Although heart rate data was collected prior to and after the six minute walk with both devices, there was no other quantitative data collected from the participants besides a perceived respiration effort. Perceived respiratory exertion and self-perceived dyspnea levels makes this study difficult to compare to the present knee crutch study. Additionally, participants who were in better shape than others may have perceived little change in effort, while their metabolic rates may have shown a significant change. However, the results show the greater metabolic and physiological stress that traditional crutches impose on the user's body.

A study conducted in 2016 compared walking with a walker, traditional crutches and a knee scooter (Patel et al., 2016). Participants ambulated with each device for 3 minute trials at a fixed speed of 1 km/hr on a treadmill. Table 1 below is a collection of average metabolic and physiological data collected in the 2016 study and the final 30 second averages of each current knee crutch trial in the present study.

Table 1: VE, VO_2 and HR data from Patel et al. (2016) and the present knee crutch study

	VE (L/min)	VO_2 (L/min)	HR (BPM)
Walker	32.8	1.2	108.5
Traditional Crutches	31.2	1.2	119.6
Knee Scooter	18.8	0.6	93.8
Knee Crutch (female)	25.98	0.514	99.1
Knee Crutch (male)	43.26	0.931	128.6

Based on the data in Table 1, it is evident that the knee caused the least cardiovascular stress among each trial. During the trial without wearing an assistive device, the final VO_2 average for the female participant of the knee crutch study was .543 L/min, and the average VO_2 for the participants in the 2016 study was .5 L/min. When compared to the knee crutch and knee scooter VO_2 values reported in Table 1, it is apparent that both are extremely similar to walking without assistive devices, making them both viable options for individuals necessitating a non-weight bearing assistive device.

Traditional crutches and knee scooter usage was compared in another study, but instead at a self-selected walking pace over the course of six minutes for each trial (Kocher et al., 2016). Trials conducted while utilizing the knee scooter accumulated an average of 229.5 more meters traveled during the six minutes when compared with traditional crutches (Kocher et al., 2016). Furthermore, the results of this study showed an average heart rate of 129.1 BPM for the traditional crutches and 109.0 BPM for the knee scooter (Kocher et al., 2016). These values are quite similar to the heart rate values recorded for both male and female participants in the knee crutch study, as shown by Figure 5, denoting similar physiological stress of each assistive device.

In a 1980 study studying oxygen consumption, three types of crutches were evaluated: elbow crutches, traditional crutches and Canadian crutches (Dounis et al., 1980). Each participant ambulated at a self-selected pace for six minutes with each assistive device in an attempt to reach steady-state exercise and observe a plateau in data (Dounis et al., 1980). The Canadian crutches, a variation combining aspects of both traditional and elbow crutches, accumulated the lowest VO_2 values, followed by the traditional crutches (Dounis et al., 1980). Average VO_2 values for the Canadian crutch trial ranged between 1.089 L/min and 1.764 L/min, VO_2 values for the traditional crutch trial ranged between 1.240 L/min and 2.007 L/min, and VO_2 values for the elbow crutch trial ranged between 1.368 L/min and 2.214 L/min (Dounis et al., 1980). The data from this study was represented in mL/kg/min, so precise averages remain unknown as they are fully dependent on participant body mass which ranged between 55.6 kg and 90 kg (Dounis et al., 1980). Nonetheless, these reported VO_2 values can be compared to the final averages collected from this knee crutch study, and it is found that the knee crutch resulted in the lowest VO_2 values, indicating the body undergoes less metabolic stress when using the knee crutch compared to the other assistive devices.

A strength found in this knee crutch study is that the trials took place on completely separate days This allowed for the trials to be completely independent of one another, and made it so rest time was not a necessary variable to account for. Another strength of this study is that the two recruited participants were both relatively healthy, which helps to limit the chance of confounding variables affecting the results of the study. Additionally, the participants were given time to practice on the knee crutch prior to the day of testing. Due to the learning curve of using the knee crutch, this practice makes the findings potentially more applicable to populations who have to use the knee crutch for several days or weeks, and grow very familiar with knee crutch ambulation during this time.

There are several limitations present in this knee crutch study. Firstly, the case study sample size potentiates issues as far as replicability of the study itself. With such a small sample size, there is an increased potential for bias and outliers that could not have been detected when studying two individuals. One limitation is that the participants were not made to fast from eating for a length of time before the study. This could mean there was some thermal effect from food that could have potentially enhanced the VO_2 values recorded by the K4 b^2. Another limitation is that many potential users of the knee crutch may be geriatric patients or have preexisting health conditions. This limits the generalizability of these study results because the subjects chosen were young, healthy individuals. Applicability of the study results is limited by the distance traveled by the participants and the amount of rest taken between trials. In a real scenario where an individual has an ankle injury, it may be necessary to walk around for longer distances than the participants needed to for each trial. In addition, the patient using the knee crutch will likely be using the assistive device for longer than a single day. The O_2 consumption and heart rate data would likely change over the span of a week or a month of the participant using the knee crutch as they gain experience ambulating with the device, once again limiting the application of the study results to a smaller population. A limitation can be found regarding the gait speed of the participants, as this was not standardized between participants. In future studies, it would be important to ask the participants to report their perceived exertion. This would have made this study easier to compare to other previous research that included participant perceived exertion and would clarify differences seen in metabolic and physiological data based on how much the participants were exerting themselves. Finally, another limitation is exemplified by only recruiting participants within the School of Health Sciences. Students within this school of study are potentially more likely to be conscious of their overall health and fitness. Because of this, the two individuals selected as participants may have had a physiologic or metabolic advantage over the general college-aged population.

Overall, the knee crutch provides another option that might be a feasible alternative for a wider range of patients who have a below-the-knee injury. Not only can utilizing the knee crutch allow for greater independence as the upper extremities can freely move during ambulation, but it has also been shown to have lower metabolic and physiological stress when compared to other assistive devices that have been studied in previous research. The methods and results of this study can be utilized as a backbone for future research conducted within the rehabilitation field to allow for the most effective use of assistive devices in allowing patients to heal efficiently from lower extremity injury.

Appendix A:

Assembly of the K4 b^2 involved a blue rubber mouthpiece, fully covering the nose and mouth. The turbine was inserted into a white, hollow plastic cylinder with a black cord that gets attached to the K4 b^2 unit. A white end cap is screwed snuggly on top of the white cylinder to conceal the turbine. The heart rate probe is attached to the K4 b^2 unit, and will receive the signal transmitted by the polar heart rate monitor belt. The sampling line is also attached to the K4 b^2 unit, and will be inserted into the white cylinder that houses the turbine once the participant is wearing the mask, and after room air calibration has been performed.

Calibration of the O_2 consumption gas analyzers within the instrument utilized the room air O_2 and carbon dioxide (CO_2) content (20.9% O_2 and .04% CO_2) (COSMED, 2011). Then, the instrument was calibrated to the tank of reference gases (16% O_2 and 5% CO_2) (COSMED, 2011). In addition, the ventilation turbine was calibrated by means of a three liter syringe, pushing and pulling three liters of air through the turbine eight times for successful calibration (COSMED, 2011).

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