# The influence of lower-limb prostheses technology on Paracanoeing time-trial performance.

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## Abstract

Within the Paracanoeing discipline, it is important to ensure appropriate control is achieved by a paddler with a disability. However, this Paralympic Games discipline has seen very little attention to date. The aims of this study were to understand the kinematic impact to a paracanoeist when not utilising the use of a prosthetic lower-limb. A kayaker with a uni-lateral transfemoral amputation completed several 200m maximal efforts both with and without their prosthesis. When the prosthetic limb was removed, there were significant differences found in stroke rate, stroke speed, stroke length and overall power output. Sagittal and frontal video analysis demonstrated the residual limb movements when paddling and indicated where support would be required to improve the kayak's control. It is recommended that those with lower-limb absence wishing to paddle a kayak competitively utilise the use of a prostheses designed for the kayaking environment that supports the residual limb at both the upper and inner thigh and the distal end.

## Implications for Rehabilitation

- This paper is the first study to investigate both biomechanical and assistive technology-related issues in the new Paralympic Games sport of Paracanoeing.

- For participants possessing lower-limb absence, a prosthetic limb that is designed specifically for the kayaking environment is recommended when Paracanoeing to maximize efficient propulsion.
- Use of an ergometer and multiple 2D cameras provides practitioners the ability to optimize both the comfort and fit of a prosthetic limb.
- Use of an ergometer and multiple 2D cameras provides both athletes and practitioners the ability to optimise the points of human contact within a kayak to ensure comfort and control.

Keywords: Prosthetics; amputee; kayaking; paracanoe; equipment adaptation

**Background**

'Paracanoe' as a sporting discipline first featured at the Paralympic Games in 2016 [1]. Whilst the sports of both canoeing and kayaking are sometimes incorrectly used synonymously or interchangeably, Paracanoe is essentially the paddling of a kayak using adaptive equipment or assistive technology by an athlete possessing some level of disability. Kayaking is one of two disciplines competed in, by both genders, over a flat, straight 200 m race course [2]. The inclusion of this sport in elite sport will increase the need for knowledge to improve an athlete's performance. However, in the case of those possessing limb absence, there has been extremely limited peer-reviewed research in this discipline at all to date [3] [4]. In the Paracanoeing event, athletes are classified into the three following categories [5] [1]. These are:

1) LTA: Kayakers that are able to use legs, trunk and arms to propel the craft.
2) TA: Kayakers that can use trunk and arms to propel the craft.

3) A: Kayakers that only have use of their arms to propel the craft.

However, it is accepted that even within these three categories, there will be large individual physical differences [6]. As a result, any adaptations to their kayak equipment will vary dependent on their individual impairment [5].

It is generally accepted that in kayaking disciplines, kayak set-up is carried out on a trial and error basis [7] and the main goal centers on the comfort of the kayaker but not necessarily the mechanical efficiency of paddling the boat [7,8]. For kayakers with a disability, comfort is equally as important as it is for non-disabled kayakers [9]. However, mechanical efficiency is also similarly important in order to compete at the highest levels [7] and is arguably more difficult for kayakers with a disability to achieve with their personal needs [10]. It seems to be the case that adapting kayaks for an athlete's specific need can vary greatly based upon the individual nature of their disability [9]. An example of this is three different methods of adaptation provided by the governing body for kayakers with an amputation [9]. When looking at these suggested methods, it is clear that they provide different levels of support through a variety of methods. The first one provides support for a short distance around the residual limb in all directions. This in essence is a shortened and modified socket typically found on clinical prostheses. The second method provides support underneath the residual limb and at the distal end. In contrast, the third method provides a tube of rigid material with a ratchet system that surrounds the residual limb, but does not provide support at the distal end. However, these differences are not seen in the recommendations of contact points required in the boats of able-bodied paddlers. In such cases Whiting and Varette [11] suggested several necessary contact points in order to have full control over a kayak. These include the lumbar back, gluteal region, hips, thighs, knees and toes. Without these contact points, it can be assumed that the kayaker will not be in full control over the kayak. Therefore, a lower-limb amputee who cannot meet all of these contact point requirements will not be in full control of their kayak without technological adaptation. This suggests that the use of some form of prosthetic limb or assistive technology may be essential but this has not been investigated.

Ong et al. [7] have previously identified that kayak setup does not have a defined process and is usually based upon trial and error. For those possessing limb absence, further investigation is needed in order to achieve the control that Whiting and Varette are referring to [11] and see how this may apply to those requiring the use of a prosthetic lower-limb.

Therefore, the aims of this study were to investigate the kinematic impact of not having the residual limb correctly supported  through use of a prostheses and to identify where a residual limb of a lower-limb amputee may require support.

## Method

### *Participant*

A 30 year old male (height: 1.73m, weight: 86.5kg), recreational-level kayaker with four years of kayaking experience and a uni-lateral transfemoral amputation was the basis for this case study. The participant used their clinically prescribed prostheses for the appropriate tests. The participant was instructed to undergo normal training and diet during the testing period, which took place over two sessions separated by a gap of two weeks to allow full recovery between them. Participant consent and institutional ethical approval was obtained prior to data capture taking place.

### *Experimental protocol*

Two separate testing days took place to capture the data. Each day comprised four maximum effort 200m paddles performed on a kayak ergometer (KayakPro, USA). Each 200 m time-trial was separated by a minimum rest period of 45 minutes. The 200m distance was selected as it represented the athlete's paracanoe class competition distance. The rest periods between trials replicated the competition structure used at the Rio Paralympic Games. Four non-randomized trials were selected due to the race schedule faced by athletes at Paracanoeing international competitions. For the first visit, the participant used their normal walking prosthesis. The second visit required the participant to paddle without the aid of their prosthesis. A test familiarization was incorporated into visit one, based upon the participant's habituation with previous testing protocol and equipment. Familiarization involved kayaking at a self-selected cadence on the kayak ergometer. The participant followed a warm-up protocol involving a five minute self-selected low-intensity effort. The participant then performed four maximum effort 200m time trials. Each time-trial involved the measurement of stroke-rate, stroke-length, time and power output. In addition, a 2-dimensional camera system (Fujifilm HS10 at 210Hz) focused on visible markers positioned on the both the hip and knee and were recorded in both the sagittal and frontal plane (Figure 1).

[FIGURE 1 NEAR HERE]

The biomechanical measures were taken from the video cameras by tracking retro-reflective markers using Quintic v26. Markers were located on the lateral aspect of the distal end of the femur on the residual limb and the greater trochanter and visible from the frontal and sagittal view cameras (Figure 1). The tracking of the markers from side and front view were digitized to allow traces of the markers movements to be observed (Figure 2).

[ FIGURE 2 NEAR HERE]

### *Data processing and analysis*

Using SPSS v21, two-way repeated ANOVA was conducted to analyze differences between the left and right side stroke length for each of the four tests, with and without the use of the participant's prosthetic limb. The data was corrected where necessary for sphericity and post-hoc Bonferroni were calculated. The difference in 200m time was assessed using Wilcoxon Signed Ranks Test.

## Results

### *200m Time*

There was no significant difference identified in the time taken to complete 200m with the prosthetic limb ($52.42s^{+/-0.82}$) compared to without it ($49.98s^{+/-0.55}$, (Z=-1.841, $p$=0.066). This demonstrated that no training effect had taken place between the trials and that they could be compared for technique as they were not statistically significant from each other.

### *Stroke Rate*

Mauchly's test indicated that the data for stroke rate was spherical, $\chi^2$ (5) = 5.576, $p$=0.350. The results show that the four trials had no significant effect on stroke rate, $F$ (3,126)=1.919, $p$=0.130. This indicated that there was no change in stroke rate within each set of the four trials (Figure 3a). Post-hoc Bonferroni calculations showed that there was no difference within the trials ($p$=>0.1).

The use of a prosthetic limb had a significant effect on stroke rate, $F$ (1,42)=4.969, $p$=0.031. Post-hoc Bonferroni also showed that there was a significant increase in stroke rate without use of the prosthesis (3.578Hz (±1.707), $p$ =0 .031).

***Power Output***

Mauchly's test indicated that the power generated per stroke (PPS) was not spherical, $\chi^2$ *(5)*=35.805, $p$=< 0.0001. A Greenhouse-Geisser correction was used. The results show that the four trials had a significant effect on PPS, $F$ *(*2.096, 88.037)=34.860, $p$=<0.0001, illustrating that there was a significant decrease within each set of the four trials (Figure 3b). Post-hoc Bonferroni showed that the first trial for PPS was significantly different to all subsequent trials ($p$=<0.001). There was no difference between the other trials ($p$=>0 .05).

The of a prosthetic limb had a significant main effect on the participants power output, $F$ (1, 42)=105.617, $p$=0.000. Post hoc Bonferroni showed that there was a significant increase in PPS without the prosthesis (39.173W (±3.856), $p$= <0 .0001) (Figure 3b).

***Stroke Speed***

Mauchly's test indicated that data for stroke speed was not spherical, $\chi^2$ (5) = 37.425, $p$=0.000. A Greenhouse-Geisser correction was used. The results show that the four trials had a significant effect on stroke speed, $F$ *(*2.010, 84.425) = 29.182, $p=0.000$. This demonstrated that there was a reduction in stroke speed within each set of the four trials (Figure 3c).

The use of a prosthetic limb had a significant impact on stroke speed, $F$ (1, 42)=113.066, $p$=<0.0001. Post-hoc Bonferroni showed that there was a significant increase in stroke speed without the prosthesis (0.268$ms^{-1}$ (±0.024), $p$=<.0001).

[FIGURE 3 NEAR HERE]

***Stroke Length***

Mauchly's test indicated that the results for the Left Stroke Length (LSL) and Right Stroke Length (RSL) were both spherical. *LSL:* $\chi^2$ (5)=8.579, $p$=0 .127 RSL*:* $\chi^2$ (5) = 3.50, $p$=0.623. The results show that the four trials had a significant effect on the stroke length on both sides, for *LSL: F* (3,126)=11.345, $p=<0.001$ (Figure 4a)*;* RSL: F (3, 126)=10.218, $p=<0.0001$ (Figure 4b). This demonstrated that there was a reduction in stroke length over the course of the four trials. Post-hoc Bonferroni showed that the first trial for LSL was significantly longer than in subsequent trials ($p$ =0.002). There was no difference between the other trials ($p>0.05$). The first trial for RSL was significantly longer than in subsequent trials ($p$=0.003). There was no difference between other trials ($p=>0.05$).

The use (or not) of a prosthetic limb had a significant impact on both sides: LSL *F* (1, 42) = 23.273, $p=<0.0001$, RSL: *F* (1,42)=10.936, $p$=0.002. Post-hoc Bonferroni showed that there was a significant mean decrease of $91mm^{+/-19}$ for the LSL ($p=<0.0001$) without the prosthetic limb. There was also a significant mean decrease of $69mm^{+/-2.2}$ for the RSL ($p$=0.002) without the prosthesis.

[FIGURE 4 NEAR HERE]

***Video analysis***

Using the videos from the frontal and sagittal plane of the kayaker (Figure 1 and Figure 2) the knee and hip marker of the left leg were tracked to show their movements both with and without the prosthetic limb fitted. Figure 5 shows the anterior view of the knee movement. With the prosthesis fitted, the graphs (Figure 5a-d) show a predominately vertical movement. There is more movement in the residual limb when it is unsupported with no prosthesis (Figure 5e-h). This tends to be towards the center line of the body and upwards towards the abdominals (Figure 2).

[FIGURE 5 NEAR HERE]

[FIGURE 6 NEAR HERE]

[FIGURE 7 NEAR HERE]

Looking at the athletes left side whilst wearing the prosthesis (Figure 6a-d), the knee moves in a linear fashion. As fatigue increases in the last trial (Figure 6d) there is a noticeable increase in the variation of the movement shown with more forward-backward variation. Without the prosthesis fitted, there is a lot more movement of the limb (Figure 6e-h). The distal end of the limb tends to move in circular pathways. The vertical displacement is also replicated in the frontal view (Figure 5e-h).

The forward-backward variation shown in the knee (Figure 6) shows that with nothing to push against, the kayaker is slipping in their seat. This is further highlighted by the forward-backward movement of the hip (Figure 7). With the prosthesis (and with fatigue over the course of the trials), there is an increase in movement of the hip in the seat (Figure 7a-d).

This is exacerbated without the prosthetic limb (Figure 7e-h) with an increased amplitude to the movement over the course of the trials.

## Discussion

There was a lack of statistical significance in the 200m completion time between the two conditions. Therefore, this supports the notion that if the completion time between the two conditions was the same, the performance of the trials can also be judged as the same. This would be supported by other studies also using race time as an indicator to determine the absence of a protocol learning or training effect [12,13].

To maintain overall kayak velocity (and thus having the same race time), the participant would have had to adapt their paddling technique if they chose to utilise a prosthetic limb or not. Haywood and Getchell support this notion by suggesting that an equipment change can lead to a change in paddling technique [12]. The change in technique experienced by the participant is demonstrated through the significant change in stroke rate, stroke length, power output and the degree of variability demonstrated in these factors.

The participant's stroke rate within the trials and between the two conditions saw no significant difference thereby demonstrating that it did not change with time or fatigue over the trials. Over both trials, the stroke rate remained within the reported range of World Champion K1 kayakers of 144-168 strokes per minute [14].

However, the 'without prosthesis' condition did have an impact on the stroke rate and increased it by an average of $3.578\text{Hz}^{+/-1.70}$. Figure 3a shows that this increase was achieved by a large increase in the deviation of the stroke rate. This demonstrates that the participant had an erratic stroke rate and indicated that the loss of their prostheses was having a detrimental effect to the stroke rate in general. This supports the proposal that the best paddlers are those with a rhythmic, rather than a faster stroke rate [15]. This suggests that although the recreational participant did obtain a stroke rate similar to that of elite paddlers, the lack of rhythm in the 'without prosthesis' condition suggests that this may not be of positive benefit to the participant. This supports that use of a prosthetic limb provides stability in the stroke quality.

The erratic behavior shown in the stroke rate (Figure 3a) is further emphasized in the power output (Figure 3b). There was a difference between the first trial and the subsequent trials both with and without prosthesis. This demonstrates the lack of experience of a recreational kayaker that would not be expected from an elite level kayaker used to racing in this format. Without the prosthesis however, there was an average increased power output of $39.173W^{+/-3.86}$ per stroke. Despite this significant increase in power, there was no overall difference in time to complete 200m between conditions. This indicates an efficiency loss when not utilizing a prosthetic limb to stabilize the paddler [16]. The lack of support for the residual limb means that the athlete had to work considerably harder in order to achieve the same power output.

The participant demonstrated that over the four trials, their stroke speed and stroke length decreased. This demonstrated some degree of physiological fatigue. However, when looking at the 'without prosthesis' condition, there is a significant increase in stroke speed of $0.268ms^{-1+/-0.02}$ and a significant decrease in stroke length (LSL: $91mm^{+/-19}$, RSL: $69mm^{+/-2.2}$). Both stroke speed and stroke length are related to the stroke rate, and therefore as an increase in stroke rate was observed, it would be expected that stroke speed would also increase as the stroke length reduced. This link between these measures can also be seen when relating stroke rate and length to the overall time when swimming [17] whereby average speed is calculated as the product of average stroke length and average stroke frequency. Therefore, as the 200m time remained the same and stroke length reduced in this paper, the stroke rate would have needed to have increased in order for the athlete to maintain the same overall time.

The impact of the lack of a prosthetic limb (and therefore the proposed need for support of the residual limb) can clearly be seen through the biomechanical measures presented here. The participant displayed more erratic and less efficient behavior, suggesting that in order to maintain the same race time, more effort was required to achieve it. Therefore in pursuit of enabling more force to be applied to a kayak [7], it is important to understand where specifically the residual limb needs to be supported. It is accepted in most cases, that due to the fit, safety and reliability, that clinically prescribed prostheses designed for everyday purposes (such as walking) are not acceptable to be used in competitive sport [18]. In addition, the sports specific guidance provided by the governing body varies greatly [9]. As a result, whilst there is an argument that reduction in the overall athlete/watercraft total mass could improve the crafts acceleration off a start line (and therefore warrant weight saving through rejection of prosthetic limb use), for paracanoiests with a lower-limb absence, this should not be made at the expense of providing appropriate levels of support to the paddler. A specialized prosthetic limb is likely warranted and will require specific attention to identify where each individual will require the most optimum level of support.

In the case of the participant in this study, it was clear that the residual limb moved at greater amounts when without prosthetic support. This reinforced the necessity to have contact points between the paddler and the craft in order to maintain control [11]. In the case of this study, the lack of a prosthetic limb support resulting in the paddler losing contact at their hip, thigh, knee and toe on the left leg and therefore would have less control over their kayak.

When looking in more detail at the direction of movements of the residual limb, it can give us an indication of where technological-based support is required for this athlete. When looking at the anterior view it is clear that the residual limb moves upwards and inwards towards the center line of the body. This suggests that support is required on the inner and upper thigh in order to act as a brace for the kayaker. This supports the third method of kayak adaptation recommended by the governing body [9] and is a rigid tube with a ratchet system. The first method of adaptation, the shortened socket, also goes some way to address this, but does not provide enough support for the thighs.

When looking at the lateral view, the lower-limbs can be seen alternating between moving forwards and backwards. This forwards and backwards movement of the knee (in comparison to the ‘with prosthesis’ condition) is significant and demonstrates a clear need for support at the distal end of the residual limb in order to stop slippage in the seat. The prevention in seat slippage will in turn reduce the movement in the hip due to its location in the paddler’s kinetic chain. When looking to the governing body’s' first and second recommendations [9], both of these indicate the need for support at the distal end. However the recommended rigid tube with ratchet system (which would be best for inner and upper thigh support), is missing this vital distal end support. Therefore, it can be assumed that none of the individual recommendations made to adapt the boat for lower limb amputees by the ICF [9] are currently appropriate for this participant and do not fully meet Whiting & Varette’s [11] suggested contact points within the kayak.

It is recommended that use of a video camera and a kayak ergometer will assist coaches wishing to identify the appropriate support requirements for those with limb absence looking to paddle a kayak and would help prosthetists’ when designing and fitting a prosthetic limb. This would ultimately reduce the proposed trial and error method of boat setup [7] and allow for the design and refinement of suitable technological solutions specific to competitive sport with a disability [18].

## Conclusion

The investigation into Paracanoeing is a new elite sport and an under-investigated field. A kayaker possessing lower limb absence undertook a series of maximal effort 200m time trials on an ergometer both with and without the use of a prosthetic limb to assess the value of the technological support it provides. When paddling without a prosthetic limb, the participant saw an increase in both their stroke speed and stroke rate. However, the participants stroke length and power output reduced. In addition, the lack of use of a prosthetic limb resulted in increasingly erratic stroke length, stroke rate and power output and therefore would demonstrate a lack of full control of their kayak. It is recommended that those with lower-limb absence wishing to paddle a kayak effectively utilise the use of a prosthetic limb designed for the kayaking environment that supports the residual limb at both the upper and inner thigh as well as the distal end.


## Acknowledgements

The authors wish to thank the athlete that participated in this study.


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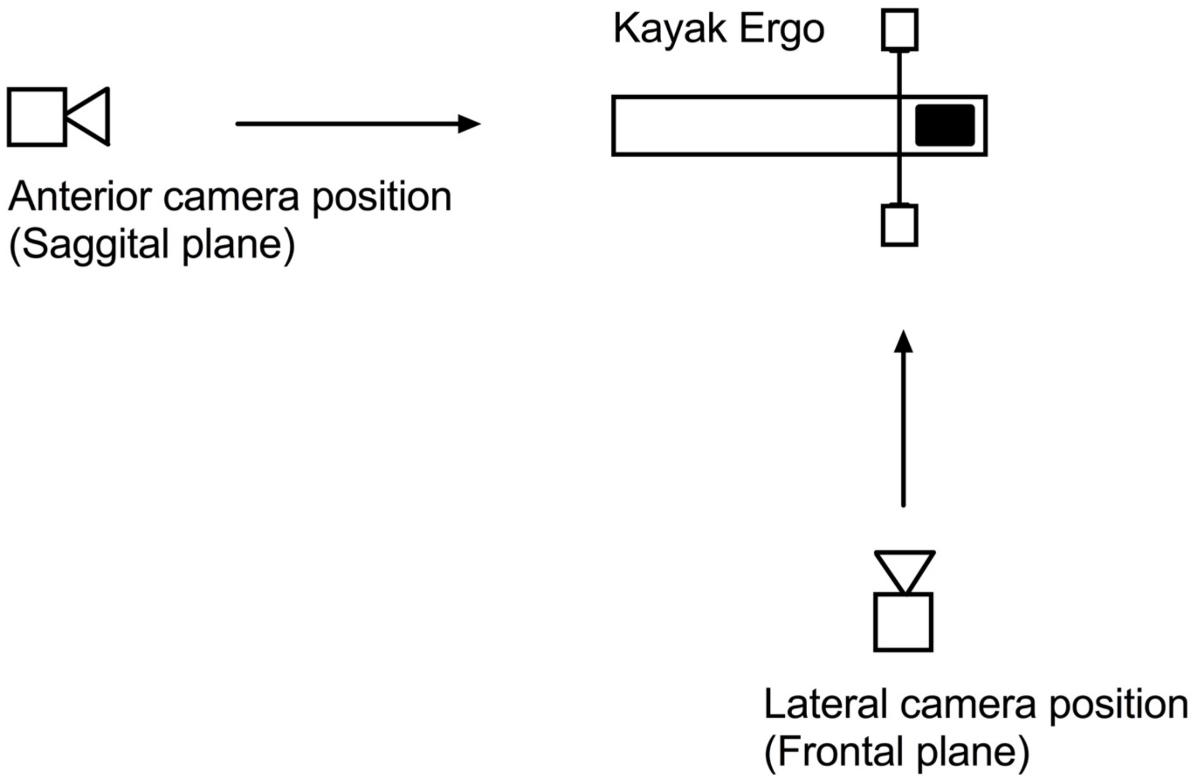
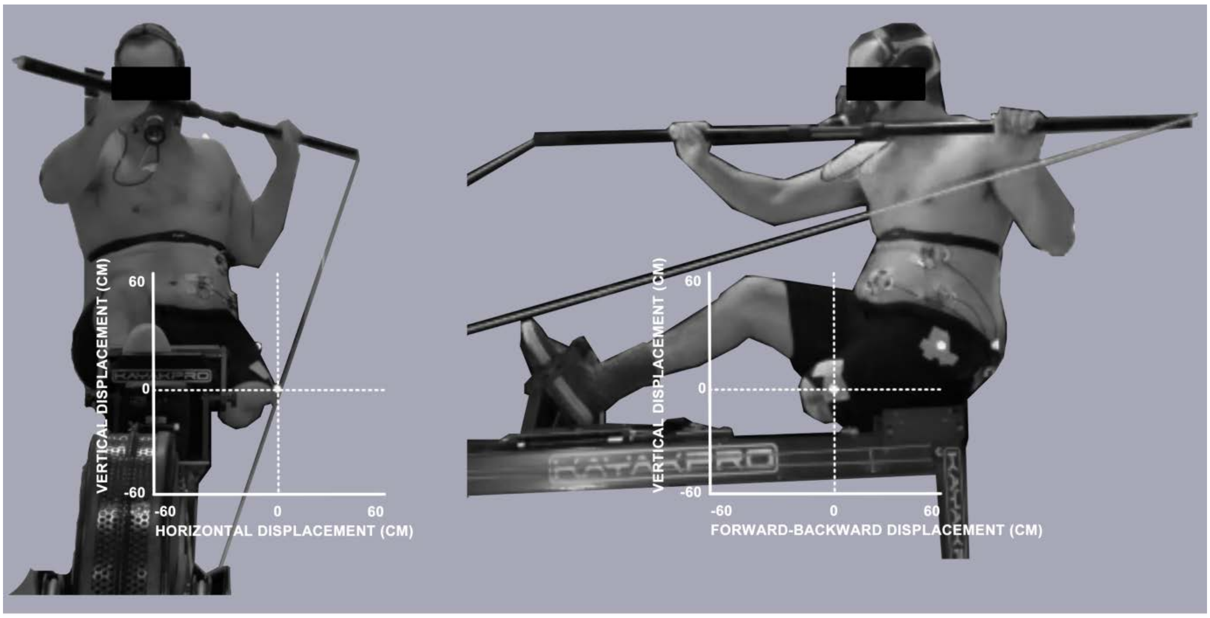



**Figure 1.** Overhead view of the experimental setup showing planes.




(a) (b)

**Figure 2**. Representation of marker placement and displacement of marker in terms of anterior (a) and lateral (b) camera views.

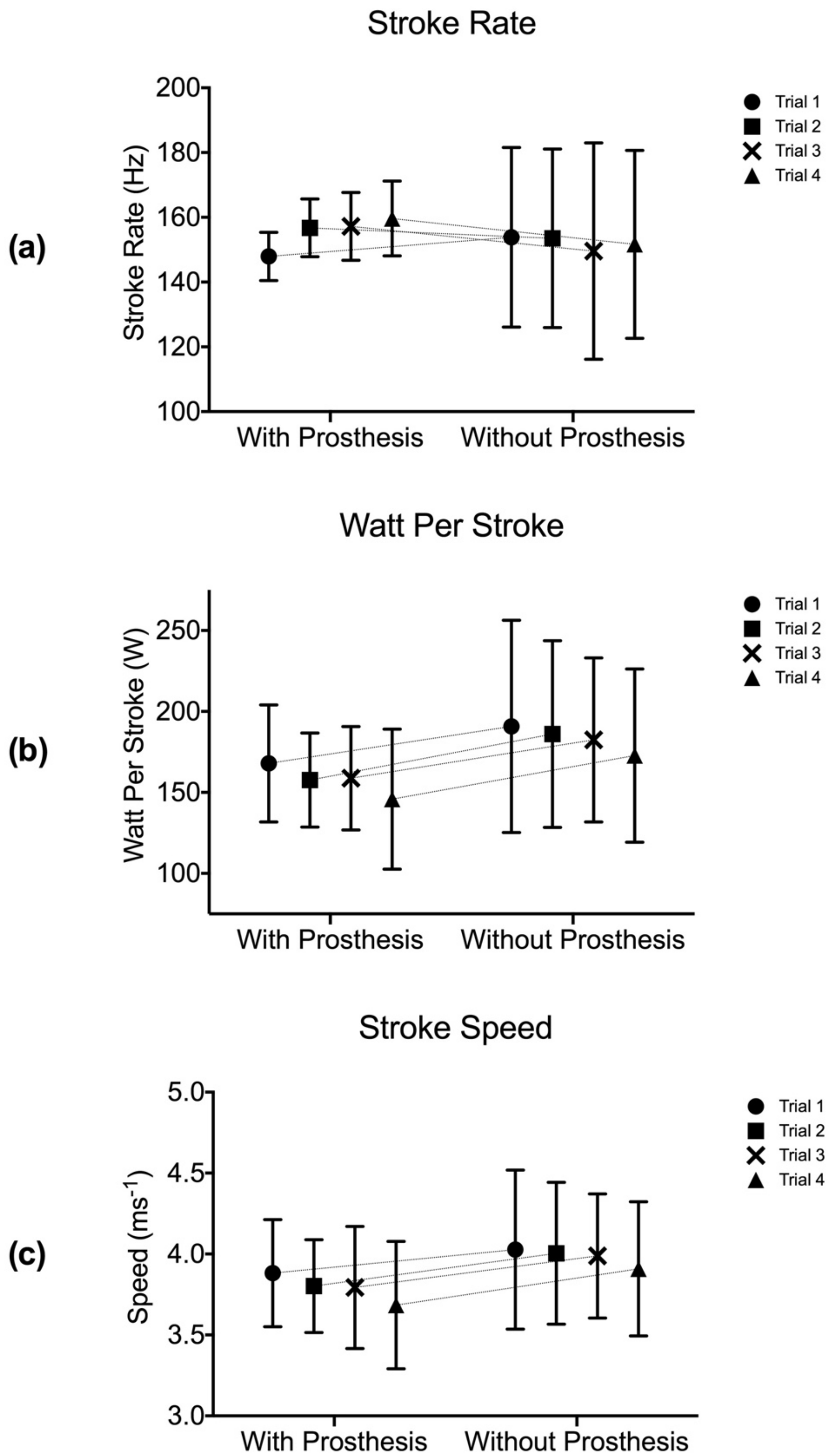



**Figure 3.** Results of (a) Stroke Rate, (b) Watts per stroke and (c) Stroke Speed with and without prosthesis.

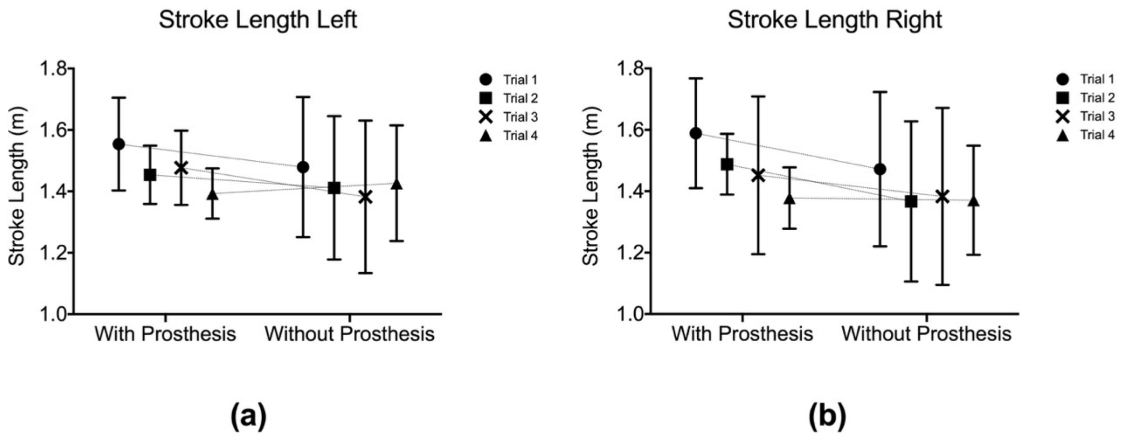



**Figure 4.** A comparison of the differences between stroke length on each side, with and without prosthesis.

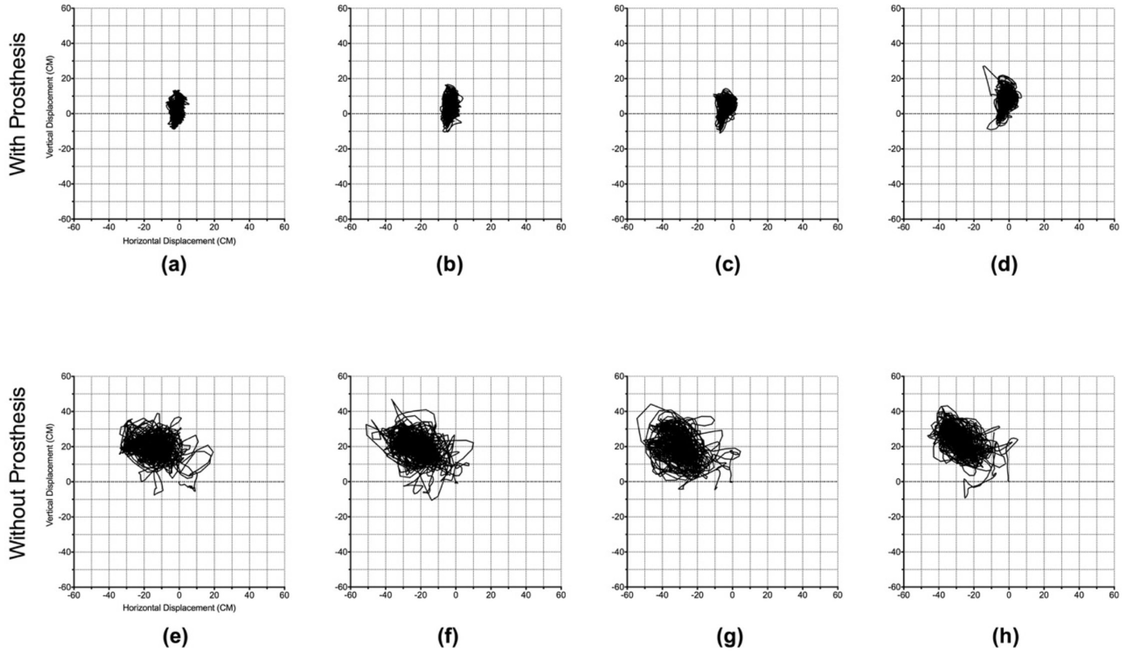



**Figure 5.** Anterior view (sagittal plane) of the knee showing vertical and lateral movement. (a-d) With prosthesis by trial number 1-4 respectively. (e-h) Without prosthesis by trial number 1-4 respectively.

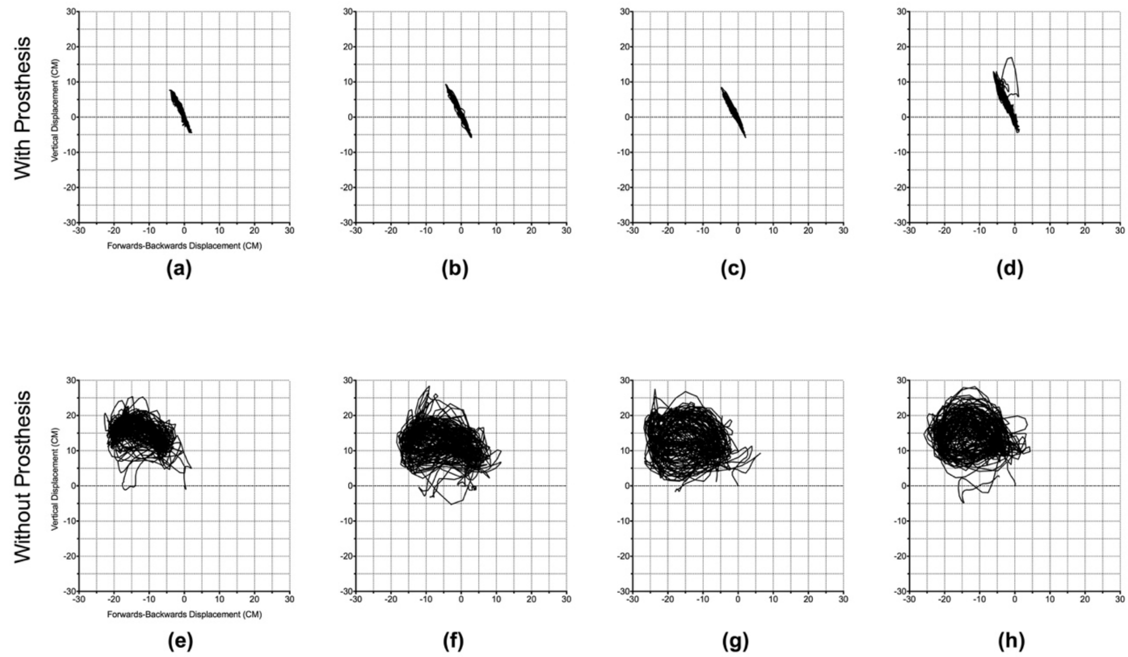



**Figure 6.** Lateral view (frontal plane) of the knee showing vertical and forward to backward (distal to proximal) movement to the body. (a-d) With prosthesis by trial number 1-4 respectively, (e-h) Without prosthesis by trial number 1-4 respectively.

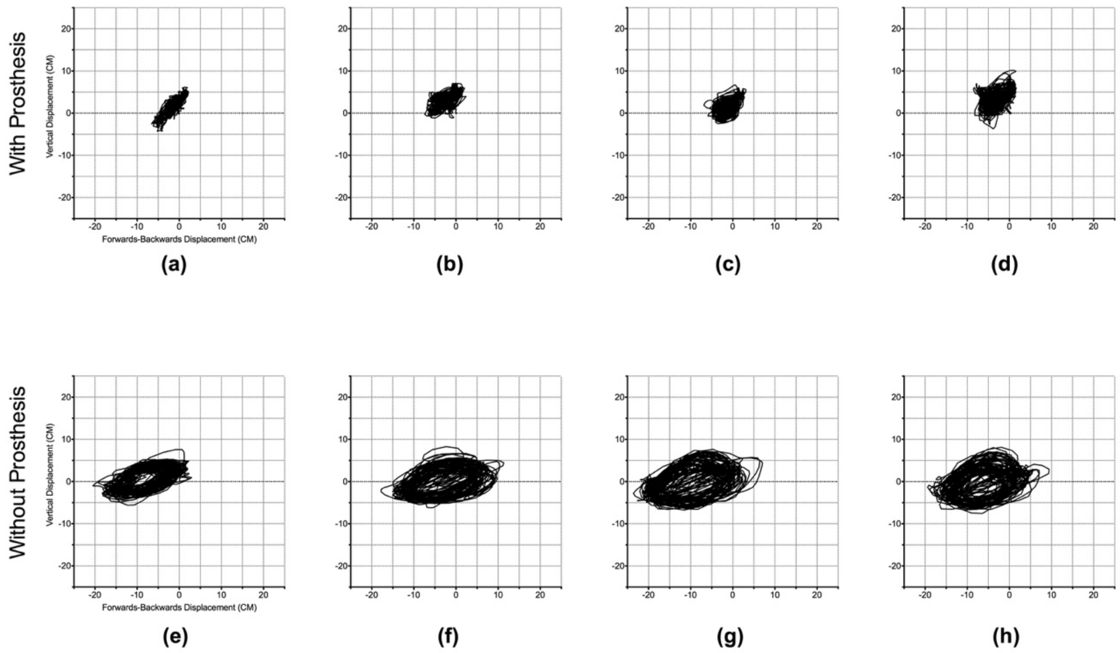



**Figure 7.** Lateral view (frontal plane) of the hip showing forward to backward (distal-proximal) movement to the body. (a-d) With prosthesis by trial number 1-4 respectively, (e-h) Without prosthesis by trial number 1-4 respectively.