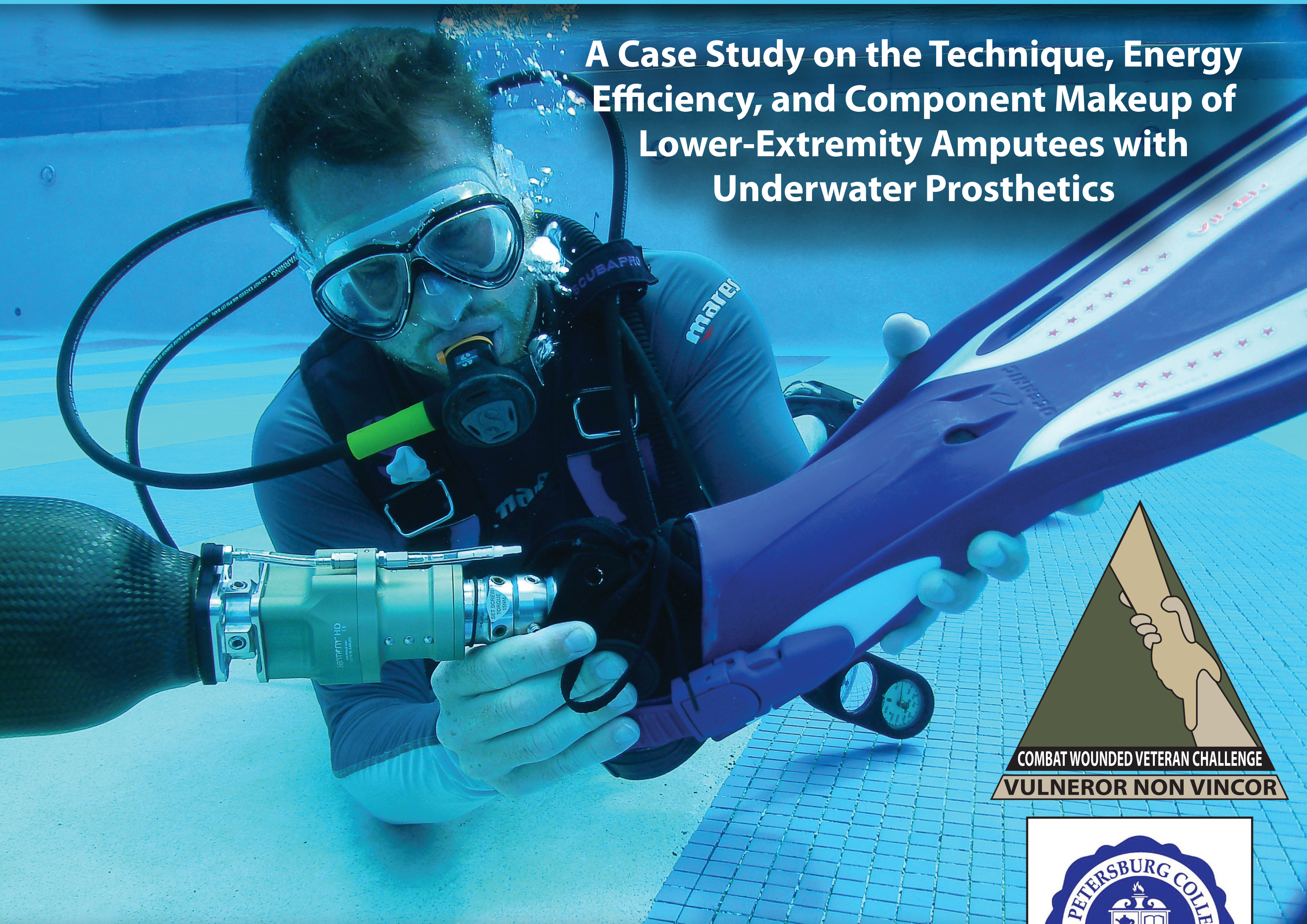
Underwater Prosthetics Case Study – 2013

COMBAT WOUNDED VETERAN CHALLENGE



A Case Study on the Technique, Energy Efficiency, and Component Makeup of Lower-Extremity Amputees with Underwater Prosthetics

COMBAT WOUNDED VETERAN CHALLENGE
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INTRODUCTION

In the field of prosthetics, we strive to get our patients back to their usual activities of daily living. Whether it be hiking, running, bicycling, or just everyday walking we push our technology to get us there. One area that we, as a field, have touched but not dived into is swimming. Sure, we can make a prosthesis waterproof to an extent and get you in the water kicking. However, it is not near to the caliber we have for other activities. In the search for the standard operating procedure of an underwater prosthesis, we must first collect data on what we already have. In finding the benefits and failures of what we have now for our amputees, we can see the road ahead much better as to what we need to improve on and how. With our field providing limited research on underwater prosthetics, this case study brings a baseline of information that we have not had before.

METHODS

Data recorded in the study included: blood pressure, heart rate, speed, energy efficiency, time and technique. Blood pressure and heart rate were taken by trained EMT's from the Key West local fire department using a Life Pact 15 Physio Control (Fig A1). Time was recorded by stop-watch and validated by video. All of the data recorded and calculated can be found on the spreadsheet (SA2013) attached to this case study.

Fig. A1

Energy efficiency was calculated from their recorded time (h), and weight (kg), and the Metabolic Equivalent (MET). MET is the measurement of intensity and rate of the activity. In this study, the activity being considered casual swimming equals a MET value of 7.0. The equation below brings us to our caloric efficiency or energy efficiency.

[Met Value (7.0) x Weight (kg) = E] [Time (Hours) x E = Calories Burned]

Video was a critical method in gaining evidence of swim techniques in this study. The case study consisted of seven video cameras. Three cameras were used as free-moving cameras and operated by members of the research team. The other four were mounted in the pool in specific locations. Two cameras were placed at the start and end of the pool giving a transverse view of the amputee's body, one camera was located on the pool floor looking straight up to the surface giving a coronal view, while the last camera was mounted on the side of the pool gaining the advantage point of the sagittal plane. The figure below (Fig. A2) gives more detail to the pool setup.

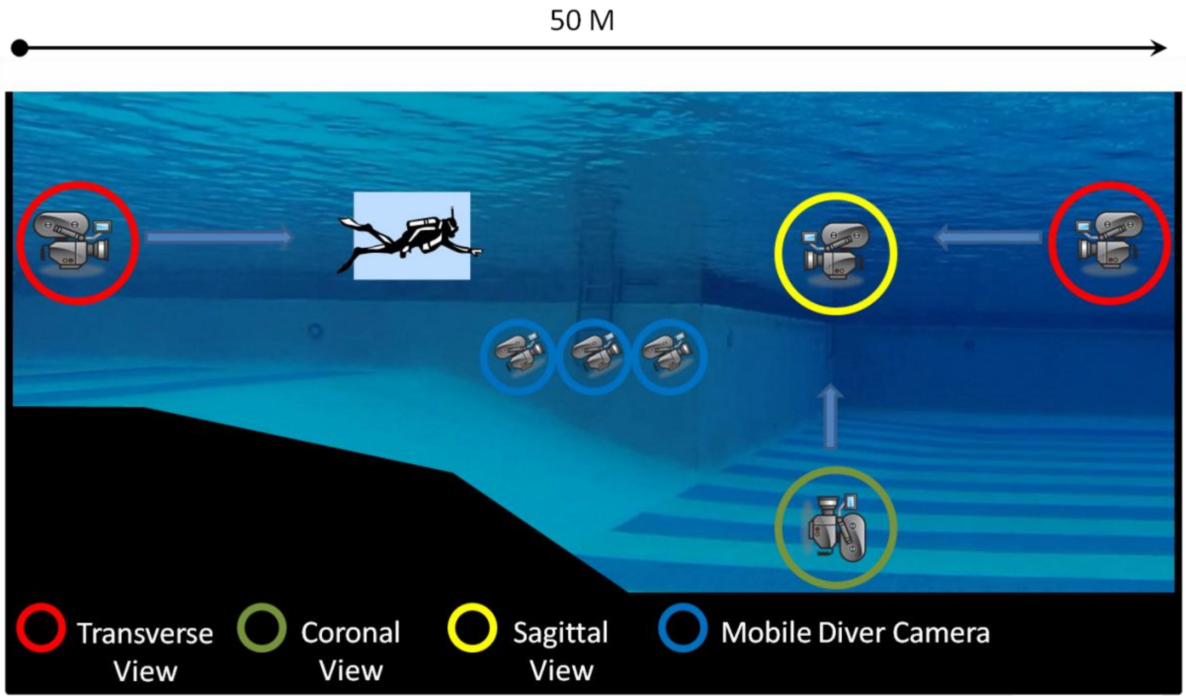

Fig. A2

Blood pressure has five categories: Normal demonstrates a Systolic mm Hg of less than 120 and a Diastolic mm Hg of less than 80. Prehypertension demonstrates a Systolic mm Hg between 120-139 and a Diastolic mm Hg of 80-89. Stage one demonstrates a Systolic mm Hg between 140-159 and a Diastolic mm Hg of 90-99. Stage two demonstrates a Systolic mm Hg between 160-180 and a Diastolic mm Hg of 100-110. Anything higher than these values is considered a Hypertensive Crisis and emergency care may be needed.

See the chart on the next page (Fig. A3) for better clarification:

Blood Pressure Category	Systolic mm Hg (Upper Digit)	Diastolic mm Hg (Lower Digit)
Normal	120	80
Prehypertension	120-139	80-89
Hypertension (Stage One)	140-159	90-99
Hypertension (Stage Two)	160-180	100-110
Hypertensive Crisis (Need Emergency Care)	180 or greater	110 or greater

(American Heart Association, 2012)

Fig. A3

SUBJECTS

This case study consists of five subjects. Of the five, one was a transfemoral amputee, two were unilateral transtibial amputees, and two were bilateral transtibial amputees. There were also three non amputees who performed the same trials. Of the amputees, their amputation dates range from two to nine years ago and all were a result of a traumatic injury. There was a sixth amputee (UBE1) who was a transradial amputee. Data was collected on him but excluded from this report since it is a lower extremity focused case study. However, you can see his data on the attached SA2013 spreadsheet. Each subject in this study used their existing swim prosthesis or prostheses fabricated by their own certified prosthetist. No changes were made to their prosthesis during the case study. Masks, fins, and snorkels were donated by Oceanic, a premier scuba manufacturer based out of the United States since 1972. Each leg was equipped with an Oceanic Viper Open Heel Fin (14.3831) (Fig. A4). All other scuba equipment including weights, vests, regulators, and tanks were rented from the local dive shop “Dive Key West”.

Fig. A4

MEASUREMENTS

One day before the study, information was collected from each amputee. Basic information such as height, weight, Body Mass Index (BMI), and amputation dates were recorded. All residual limbs were evaluated and measured for standard circumferential, medial/lateral, anterior-posterior, and length measurements. Tissue type was assessed along with range of motion (ROM) and manual muscle testing (MMT). All subjects were within normal range and scored five out of five on their MMT.

PROTOCOL

All participants were asked to swim fifty (50) meters in a casual pace dressed with full scuba equipment. One swim would be recorded with the use of prosthetics and one without. Blood pressure and heart rate were recorded before and after the swim as well as time. From those recordings, speed and energy efficiency were also calculated. Between trials, subjects were given ample time to rest and obtain a more normal blood pressure and heart rate.

Below are the individual case studies that were completed on July 28th, 2013.

CASE STUDIES

Unilateral Transtibial (Below-Knee) Trials

Case Study One - "UBK1"

UBK1 is a 53 year old male, 6'0", 210lbs (95.45kg), a BMI of 28.53 kg/m_2, with an athletic build and ambulates as a K4. UBK1 suffered the loss to his right leg below the knee in December of 2007 after complications from a thirty foot fall from the brow of the USS Enterprise to a concrete pier below. No other notable pathologies were recorded.

His daily prosthesis consists of a carbon fiber socket, a suction suspension with a sleeve, and a dynamic response foot from Ossur called the Re-Flex VSP.

UBK1's swim prosthesis consists of the same setup except for the exchange of his foot called Freestyle from Freedom Innovations. This prosthetic foot allows for 70 degrees of locked plantarflexion (PF) with the availability to lock it at 0 when the amputee is out of the water ambulating.

UBK1's residual limb is of firm tissue and long conical shape. Measurements from the mid-patellar tendon (MPT) to the distal end of the tibia were 22 cm and 23 cm to the end of the residual limb.

UBK1 became a certified diver in 1996 and dives 1-3 times a year. However, when getting into a swimming pool he chooses not to wear a prosthesis and states, “It is just easier without it”.

UBK1’s first 50 meter swim (Fig. A5) was at 10:59 am with his prosthesis. His starting blood pressure was 121/83 (Prehypertension) and starting heart rate was 95 bpm. He accomplished this task in 69 seconds without the use of his arms at a speed of 0.724 mps or 1.619 mph and by burning a total of 12.81 calories. His final blood pressure was recorded at 152/77 (Cat. 1) and ending heart rate was 101 bpm.

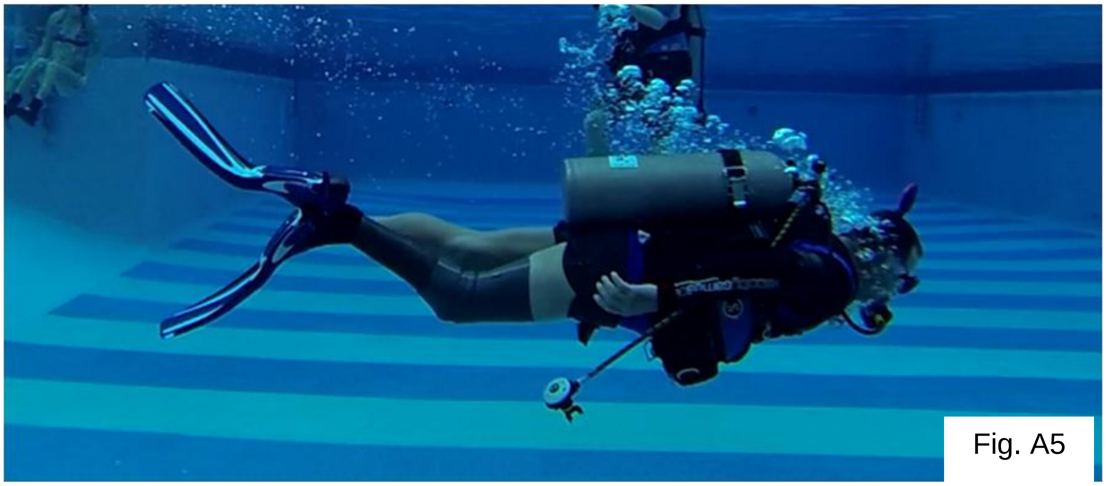

Fig. A5

His second 50 meter swim (Fig. A6) was at 11:45 am without his prosthesis and without a fin on his sound side. His starting blood pressure was 132/74 (Prehypertension) and his starting heart rate was 93 bpm. It was noted that he used his arms during this trial. He accomplished this task in 97 seconds with the use of his arms at a speed of 0.515 mps or 1.152 mph and by burning a total of 18.00 calories. His final blood pressure was 129/81 (Prehypertension) and ending rate was 118 bpm.

Fig. A6

Comparing the two trials, when using the prosthesis, UBK1's heart rate only went up 6 bpm compared to the 25 bpm increase when not using it. He was also 40.5**%** quicker and in regards to energy efficiency, UBK1 was 28.87% more energy efficient while using his underwater prosthesis.

In viewing the video footage of UBK1's swim techniques there were a few notable observations. While using the prosthesis, he exhibited 42 degrees of knee flexion on the prosthetic side while on the sound side he reached 63 degrees. This may attribute to a few different reasons. One possible reason along with other transtibial amputees could be the posterior trimlines on the socket. These trimlines, which are modeled around our medial and lateral hamstring insertion points, are most likely hindering full flexion or at least "comfortable flexion". A possible option for this would be to lower the posterior trimlines on his swim prosthesis and remeasure his knee flexion to see if this is the primary problem.

A second note would be the sleeve. In vacuum, or in this case a suction prosthesis, a sleeve is worn to create a sealed chamber. These sleeves are typically fabricated from a silicone or a gel material but could also be hindering our amputees from full ROM of knee flexion.

The third possible reason would be the amount of torque on the residual limb. When pushing down and up against the resistance of water, the residual limb inside the socket is enduring a certain amount of pressure and movement against the socket. This uncomfortable and avoidable feeling causes the amputee to switch his pattern without even knowing it. Similar to how we change the way we walk naturally if our hip, knee, or ankle might be bothering us, our gait automatically adjusts.

When viewed in the transverse plane, UBK1 showed a significant amount of hip rotation when trying to move his prosthesis down on the water or into hip flexion and knee extension. He used the force of his pelvis to thrust the leg down providing more propulsion. This is optimal in swimming but usually it is performed bilaterally creating a fluid movement. In this trial, UBK1 only uses it on the side of his prosthesis.

UBK1 conducted the 2nd trial without his prosthesis on and with no fin on the sound side but he did keep on his neoprene dive boot. While not wearing the prosthesis UBK1's legs became erratic. He kicked in a circumducted pattern and the use of his arms became the powerhouse of his speed. He constantly fought to be horizontal in the water only leveling out once he had finished his arm stroke. This was a huge difference when wearing his prosthesis because he did not have to compensate and his body was continuously in a parallel pattern to the surface above.

Case Study Two - "UBK2"

UBK2 is a 42 year old male, 6'0", 215lbs (97.72kg), a BMI of 29.21 kg/m_2, with an athletic build and is a K4 ambulator. UBK2 lost his left leg below the knee in July of 2004 after a gunshot to his lateral malleolus. No other notable pathologies were recorded.

His daily prosthesis consists of a carbon fiber socket, a vacuum suspension using the Willow Wood LimbLogic, a suspension sleeve, and a running foot from Freedom Innovations called the Sprinter. This foot is not typically worn for everyday walking but UBK2 prefers it.

His swim prosthesis is a carbon fiber socket, suction suspension with a sleeve and the Freedom Freestyle swim foot.

UBK2's residual limb is of medium tissue type and a conical shape. Measurements from the MPT to the distal tibia were 17cm and to the distal end were 25 giving him about 8 cm of soft tissue. The only other notable features include a very prominent fibula head.

UBK2 became a certified diver in 2000 and has been casually diving once every year or so since then, other than getting in the occasional pool from time to time.

UBK2's first 50 meter swim (Fig. A7) was at 10:45 am with his prosthesis. His starting blood pressure was 177/97 (Cat 2) and starting heart rate was 125 bpm. He accomplished this task in 45 seconds without the use of his arms at a speed of 1.111 mps or 2.485 mph and by burning a total of 8.55 calories. His final blood pressure was recorded at 187/107 (Hypertensive Crisis) and ending heart rate was 140 bpm.

Fig. A7

UBK2's second 50 meter swim (Fig. A8) was at 12:01 pm without his prosthesis. His starting blood pressure was 182/113 (Hypertensive Crisis) and starting heart rate was 132 bpm. He accomplished this task in 79 seconds with the use of his arms at a speed of 0.632 mps or 1.413 mph and by burning a total of 15.01 calories. His final blood pressure was recorded at 187/107 (Hypertensive Crisis) and ending heart rate was 140 bpm.

Fig. A8

It needs to be noted that one 50 meter trial, while using UBK2's prosthesis, was not included due to the fact that his fin on the prosthetic side came off about ¾ of the way through the trial.

Comparing the two trials, when using the prosthesis, UBK2's heart rate went up 15 bpm compared to only 10 bpm increase when not using it. He was 75.8% quicker and in regards to energy efficiency, UBK2 was 43.04% more energy efficient with the prosthesis. In viewing the videos of UBK2 it is important to document that his swim trials were not very casual in nature. He was the fastest of all the amputees but it was evident that he was not swimming at a very casual pace. His maximum knee flexion on the prosthetic side was measured at 41 degrees and on the sound side it measured 52 degrees. The difference between these two can also be in relation to UBK1's trials. However, the gap between the two is smaller. On his trial with the prosthesis, he not only finished with the quickest time, but he also went deeper than any other amputee causing him to swim further than 50 meters and this calculation is unable to be measured.

When not using the prosthesis, UBK2 did not use fins and did not have anything on his sound foot. He kicked his residual limb as if he still had his prosthesis on and his sound-side kicks were 3 to 1. His arms were used for a large part of his propulsion but he maintained a horizontal balance throughout the swim.

*Post study, it was brought to the attention of UBK2 of his abnormally high blood pressure recordings and that he should contact a cardiologist for testing.

Comparing Unilateral Transtibial Amputees

Comparing our small population of unilateral transtibial amputees, both were of similar height and weight but at an eleven year age difference. We first look at their prosthetics. Both of their swim legs are similar in regards to carbon fiber sockets, a suction suspension, and their swim feet. UBK1's residual limb is 5 cm longer and gives him a lead in the lever arm. Their statistics show a major difference in speed, blood pressure, heart rate, and calories burned but this is because of UBK2's "more than casual" pace during his trials. Therefore it makes it hard to compare the two in this manner. ROM's show another correlation between the two with their prosthetic side always showing a much smaller ROM in knee flexion than the sound side. UBK1's difference being 21 degrees and UBK2's being 11 degrees. On the prosthetic side, both exhibited over 50 degrees of knee flexion and if this were to be duplicated, it could result in much more propulsion. Another ROM that contrasts them greatly is hip flexion. UBK1's hip flexion ranges from 2-8 degrees with 8 being on his prosthetic side. UBK2's is 24-28 degrees with 24 on the prosthetic side. This is mainly due to their swim speeds and further research will be done as to how torque in a transtibial prosthesis can alter hip flexion.

Without the use of their prosthetics, both amputees showed difficulty in maintaining balance and had a decrease in speed and energy efficiency. Finishing just 18 seconds apart and at a mutual decrease in speed, the only thing that is interesting is their blood pressure. With prosthetics, both subjects jumped into a higher category at the end of the 50 meters and without prosthetics they both maintained the same category. So with all these statistics showing signs of increased stress and energy, they remained calm and content without their prosthetics. This is an area that will need to be confirmed in future studies. However, it is evident that both subjects were much better in almost all categories when using their prosthetics.

Bilateral Transtibial (Below-Knee) Trials

Case Study Three - "BBK1"

BBK1 is a 29 year old male, 5'8", 190lbs (86.36kg), a BMI of 28.96 kg/m_2, with an athletic build and ambulates as a K4. BBK1 suffered the loss to both of his legs below the knee in September of 2010 after stepping on a landmine overseas. No other notable pathologies were recorded.

His daily prostheses consist of carbon fiber sockets, a vacuum suspension using Otto-Bock Harmony P2 pumps with sleeves, and Freedom Highlander feet.

BBK1's swim prosthesis consists of the same setup except for the exchange of his foot to a Freedom Freestyle. He adds black lace-up Converse shoes to his setup to make a better fit into his fins.

BBK1's residual limbs are of soft tissue type and short conical shape. On his right residual limb, measurements from the MPT to the distal end of the tibia were 12.2 cm and 13.9 cm to the end of the residual limb. On his left residual limb, measurements from the MPT to the distal end of the tibia were 12.5 cm and to the distal end was the same at 12.5 cm.

BBK1 became a certified diver in 2004 and up until 2010 would dive once about every week. This case study will be his first time diving since his amputation. When getting into pools with friends and family, he prefers to not wear his prosthetics because of difficulty in changing out his feet.

BBK1's first 50 meter swim (Fig. A9) was at 10:53 am with his prostheses. His starting blood pressure was 131/74 (Prehypertension) and starting heart rate was 111 bpm. He accomplished this task in 64 seconds without the use of his arms at a speed of 0.781 mps or 1.747 mph and by burning a total of 10.75 calories. His hands were kept in front of him clasped together during this trial. His final blood pressure was recorded at 147/85 (Cat. 1) and ending heart rate was 127 bpm.

Fig. A9

His second 50 meter swim (Fig. A10) was at 11:30 am without his prostheses. His starting blood pressure was 116/61 (Normal) and his starting heart rate was 102 bpm. It was noted that he used his arms during this trial for most of his propulsion. He accomplished this task in 80 seconds with the use of his arms at a speed of 0.625 mps or 1.398 mph and by burning a total of 13.43 calories. His final blood pressure was 128/71 (Prehypertension) and ending rate was 115 bpm.

Fig. A10

Comparing the two trials, when using his prostheses, BBK1's heart rate went up 16 bpm compared to only 13 bpm increase when not using it. Both of these are impressive given the fact that this was his first time with scuba equipment since 2010 and his first time using prosthetics in the water ever. He was 24.96% quicker with his prostheses and 19.99% more energy efficient.

In viewing the video of BBK1's trials, the most eye-catching item is the inability to keep his prosthetics from sinking when wearing his prostheses. Throughout the 50 meters, he is constantly raising his hips to get his legs up. This might be because of his vacuum technology. The vacuum removes all of the air in his socket and the pump itself is between 520-640 grams for just one of them. Therefore, he has a negatively buoyant prosthesis. This was examined further in another trial and will be discussed later on in the study.

One ROM that was added in the bilateral trials is defined in this study as "spread". This ROM is taken in the sagittal plane from the greater trochanter of the visual side through both of the ankles. BBK1's spread was measured at 49 degrees. Some of this accounts towards the amount of hip flexion and extension. In this instance, the maximum amount hip flexion measured was 11 degrees and the maximum amount of hip extension was 26 degrees. This is relevant because the spread is much greater than any other swimmer that was measured and this was never mentioned during the trials therefore the amputees did not realize how much they were doing it. It is possible that bilateral transtibial amputees might feel more propulsion that way. The last ROM here is knee flexion. Again, here we see the small ROM with BBK1's maximum being 36 degrees. This number is consistent with other transtibial subjects and might also attribute to his large spread ROM.

When not wearing his prostheses, BBK1 slightly moved his residual limbs in a swim pattern and showed strong arm motions to move forward. His small movements in his legs seemed to help him maintain his balance while moving through the water. This is evident before each arm moves through the water down to his side and you can see him become less horizontal. All of his videos show a much better swimming pattern with his prosthesis.

Case Study Four - "BBK2"

BBK2 is a 35 year old male, 6'1", 221lbs (100.45kg), a BMI of 29.22 kg/m_2, with an athletic build and he ambulates as a K4. BBK2 suffered the loss to both of his legs below the knee in February of 2011 after getting hit by an Improvised Explosive Device (IED). No other notable pathologies were recorded.

His daily prostheses consist of carbon fiber sockets with flexible inner liners, suction suspension with sleeves, and Ottobock Triton feet.

BBK2's swim prostheses consist of the same setup except for the exchange of his feet to a Freedom Freestyles. In the past BBK2 has used short fins and for this study he will be using the standard fins from Oceanic that the rest of the subjects have conducted their trials with.

BBK2's residual limbs are of medium tissue type, medium length and of conical shapes. On the right residual limb, measurements from the MPT to the distal end of the tibia were 18.2 cm and 18.5 cm to the end of the residual limb. On the left limb, measurements to the distal end of the tibia were 18.3 cm and 18.7 cm to the end of the residual limb.

BBK2 became a certified diver in 1991 and estimates himself to have around 1000 dives. In the past, BBK2 has tried vacuum under the water using the Willow Wood LimbLogic but he states that it just would not hold vacuum at depth. Therefore he has used a suction system since then.

BBK2's first 50 meter swim (Fig. A11) was at 12:40 pm with his prostheses. It was noted that he used his arms at his side during this trial and that his hands were equipped with gloves that included webbing. You can see these gloves in figure A11 and figure A12. His starting blood pressure was 130/82 (Prehypertension) and starting heart rate was 107 bpm. He accomplished this task in 65 seconds without the use of his arms at a speed of 0.769 mps or 1.720 mph and by burning a total of 12.70 calories. His final blood pressure was recorded at 153/78 (Cat. 1) and ending heart rate was 113 bpm.

Fig. A11

His second 50 meter swim (Fig. A12) was at 1:05 pm without his prostheses. This time BBK2's arms were out in front of him and giving him most of his propulsion. His starting blood pressure was 137/76 (Prehypertension) and his starting heart rate was 97 bpm. He accomplished this task in 92 seconds with the use of his gloves at a speed of 0.543 mps or 1.214 mph and by burning a total of 17.97 calories. His final blood pressure was 130/82 (Prehypertension) and ending rate was 105 bpm.

Fig. A12

Comparing the two trials, when using his prostheses, BBK2's heart rate was only 2 bpm less than when he did not wear his prosthetics. He was very calm in the water and you can tell he has gone swimming before without his prosthetics. His blood pressure spiked when he used his prosthetics and was nearly the same when not using them. However, when looking at speed, He was 41.68% faster with his prosthetics on and 29.35% more energy efficient.

In viewing the video of BBK2's trials, as already noted, he used webbed gloves and small arm movements at his side during his prosthetic trials. This will play a variable in the study but did not make him faster than his other bilateral counterpart. With his prosthetics, BBK2's legs were constantly rising. This is different than BBK1 and mainly because of the use of suction. Suction cannot pull all the air out of a socket and it is coupled with a pylon instead of a vacuum unit which makes it lighter and more available to hold air. This ultimately causes it to be positively buoyant. Therefore, BBK2 aimed his torso down much more to keep his legs from touching the surface. In looking at the spread ROM, BBK2 measured 50 degree spread with maximum hip flexion being 12 degrees and maximum hip extension reaching 28 degrees. His maximum knee flexion was measured at 28 degrees and was consistent throughout his trial.

When not using his prosthetics, BBK2 continued to use his webbed gloves but with much bigger arm movements out in front of him. His residual limbs did not show much movement other than an extensor pattern in the hips. He accomplished the task just 27 seconds shorter than with his prosthetics but looked calm doing it. His balance was great and you can tell that he had done this before. It would have been more validated to have BBK2 conduct the two trials again using the same arm pattern and without gloves to gain a true understanding of the difference between his prosthetics.

Comparing Bilateral Transtibial Amputees

The two bilateral transtibial subjects in this trial are of different body styles but both of athletic build. First, let's compare prosthetics. Both of them are of very similar makeup regarding socket type, with a suspension sleeve, and the same prosthetic swim feet. The primary difference between the two is suspension: one being suction and one being vacuum. In their first 50 meter swim with prosthetics they both finished about the same time and they both jumped up into the next blood pressure category. They burned very different calories but this is due to their difference in height and weight.

Visualizations and measurements show a mutual relationship between knee flexion and spread ROM's. Knee flexion both being around 30 degrees and spreads both being around 50 degrees. The spread is such an interesting measurement and future trials will be conducted if other bilateral transtibial amputees perform the same way. BBK1 did not use his arms where BBK2 did and he also wore gloves and therefore gives us a substantial variable when comparing the two trials. The other primary distinction that was already mentioned but not compared is that BBK1's prosthetic legs were negatively buoyant while BBK2's were positively buoyant. This all falls under the makeup of the prostheses. Hands down, BBK1's prostheses are much heavier. On land this does not matter as much given that vacuum tends to make the prosthesis feel lighter than it is. However, in water you cannot stay afloat with things that are negatively buoyant. This made a huge difference in the style and balance that both of these bilateral amputees performed. Both were compensating in their own ways to maintain their body in a horizontal fashion, just in opposite directions.

Because of this fact, a third trial was conducted. High-density foam was added to both of their prosthetic legs distally just proximal to their fins (Fig. A13). As we know, foam is positively buoyant and this could assist BBK1 tremendously in swimming if it were to compensate and equal out the negative buoyancy of his prosthetic legs. The picture below shows the foam tape on to the prostheses. This was not a planned trial and improvised on-site.

Fig. A13

These two trials can also be viewed on the attached spreadsheet SA2013. When wearing the high density foam, BBK1's body was much more horizontal and he verbally said that it was much easier to do the 50 meters. He was five seconds faster without the foam on but he looked much smoother and without several swims recorded it is hard to know what his time could potentially be. With BBK2, we knew this would cause his prosthetics to float even more but wanted to try them out for a comparison. BBK2 was as slow with the foam as he was without the prosthesis and used the same amount of calories accomplishing the task. If time would have permitted, we could have added weights to BBK2's prostheses that would have made him neutrally buoyant. This additional trial proves that we can certainly alter the performance of underwater prosthetics just by making them neutrally buoyant. For the sport of scuba diving, we constantly alter our buoyancy to ascend and descend in the ocean. An adjustable buoyancy control unit for prosthetics could be beneficial in diving very similar to the buoyancy control vests we wear in the sport. However, for the everyday amputee and the therapeutic reasons of swimming, a neutrally buoyant prosthesis would be most optimal.

Unilateral Transfemoral (Above-Knee) Trial

Case Study Four - "UAK1"

UAK1 is a 30 year old male, 5'9", 154lbs (70kg), a BMI of 22.78 kg/m_2, with an athletic build and ambulates as a K4. UAK1 suffered the loss to his right leg above the knee in September of 2011 after an IED went through his knee. He underwent revision two weeks post amputation. No other notable pathologies were recorded.

His daily prosthesis consists of a carbon fiber ischial containment socket with a flexible inner liner, a suction suspension with an Ossur seal-in liner, a rotator, an Ottobock X3 knee, and an Ossur Variflex foot with EVO.

UAK1's swim prosthesis consists of carbon fiber ischial containment socket with a flexible inner liner, a suction suspension with an Ossur seal-in liner, a BOA tightening system, an Otto-Bock 3WR95 waterproof knee, and the Freedom Freestyle swim foot. In UAK1's spare time, he has experimented with different components and in this current swim prosthesis he has fabricated a leaf spring into the setup to give the knee some kick back. This setup can be viewed in Fig. A14. He also chooses to wear a waist belt while diving because of the added security of suspension.

UAK1's residual limb is of medium type tissue and long conical shape. Measurements from the ischial tuberosity to the distal end were 30.6 cm.

UAK1 became a certified diver in 2010 and was injured just a year later. However, he was a student at the Army's combat diving school and is very well trained in the sport.

UAK1's first 50 meter swim (Fig. A14) was at 10:56 am with his prosthesis. His starting blood pressure was 127/71 (Prehypertension) and starting heart rate was 86 bpm. He accomplished this task in 67 seconds without the use of his arms at a speed of 0.746 mps or 1.668 mph and by burning a total of 9.12 calories. His final blood pressure was recorded at 122/82 (Prehypertension) and ending heart rate was 112 bpm.

Fig. A14

His second 50 meter swim (Fig. A15) was at 11:38 am without his prosthesis and without a fin on his sound side. His starting blood pressure was 120/73 (Prehypertension) and his starting heart rate was 82 bpm. It was noted that he used his arms during this trial. He accomplished this task in 86 seconds with the use of his arms at a speed of 0.581 mps or 1.299 mph and by burning a total of 11.71 calories. His final blood pressure was 118/69 (Normal) and ending rate was 105 bpm.

Fig. A15

Comparing the two trials, when using the prosthesis, UAK1's heart rate increase was very similar in both trials with a difference of 3. His blood pressure during both trials remained in the prehypertension category and actually dipped into the normal range when finishing his second swim without his prosthesis on. He was 28.4% quicker and 22.09% more energy efficient with the prosthesis.

In viewing the video of UAK1, we notice that he keeps his arms to his side when using his prosthesis. With all of his propulsion coming from his kicks we have several ROM's that we can collect. On the sound side, he measures 26 degrees of hip flexion and 32 degrees of hip extension. In the sound side knee, he measures 70 degrees of flexion. This is all substantial when looking at his amputated side. The amputated side measures 31 of hip flexion, 9 degrees of hip extension, and only 7 degrees on his best kick in knee flexion.

First, let's discuss hip extension. 32 degrees compared to 9 is quite a difference. The primary reason has to be his posterior trimlines on his ischial containment socket. These trimlines are traditionally contoured to "seat" or contain the ischial tuberosity in an attempt to be a primary weight bearing point. However, in the water there does not need to be a weight bearing location. In hip extension, this carbon fiber seated right under the tuberosity, is being driven up more towards the boney lock stopping it from achieving full or even partial hip extension ROM. A lower proximal posterior trimline here could greatly benefit a more symmetrical kick and in the end create more propulsion. However, when the amputee exits the pool or the ocean, he or she is now end-bearing on the distal end of their femur. Using a flexible inner liner and specific modified trimlines, there is a possibility we could achieve the best of both worlds for this underwater prosthesis.

The second area we see is the difference in knee flexion of the sound side vs. the prosthesis. With a 63 degree difference, there is some compensation occurring. This greatly changes his propulsion for each kick and also creates problems in his balance. If we can match or at least get his knee flexion to a similar ROM, we could greatly improve his energy efficiency and effectiveness. However, this all truly comes down to the prosthetic knee. In the world of prosthetic knees, 99% of them are made for walking, standing, and achieving great things on land. The few that are made for water give you the option of locking the knee in extension or giving it free motion. Neither of these being optimal, we need a knee that can give us 15-20 degrees of flexion and then return to extension to prepare us for the next kick. The Ottobock X3 could be a knee to get us there as it classifies itself as "waterproof" and has these modes available**.** For the pool and for therapeutic exercising this might just be the next big thing in underwater prosthetics. However, we do not know the maximum depth that it can withstand for our amputees in the diving world.

The last observation is the rotation of the hips to get the maximum amount of range before pulling his prosthesis down into hip flexion. This is similar to the unilateral transtibial amputees in that they rotate their pelvis to face the amputated side before kicking down. For UAK1, this is his compensation for the limited hip extension. Because of the extra time he takes for his pelvis to rotate, his sound side knee goes into excessive knee flexion. This answers the question as to why his knee flexion is so much greater than any other swimmer. With the reduced posterior trimlines we could see an improvement in his hip rotation as well, as long as he has not already developed a habitual approach in his technique.

Non-Amputee Trials

The following trials were conducted to get a glimpse of three non-amputees performing the same task of swimming 50 meters with scuba equipment and fins.

NA1 is a 30 year old male, 6'1", 198lbs (90kg) with an athletic build. NA1's first 50 meter swim was at 12:46 pm. His starting blood pressure was 114/66 (Normal) and starting heart rate was 113 bpm. He accomplished this task in 50 seconds with the use of his arms at a speed of 1.00 mps or 2.236 mph and by burning a total of 8.75 calories. His final blood pressure was recorded at 163/133 (Stage Two) and ending heart rate was 136 bpm. Looking at NA1's swim technique, he has a maximum knee flexion of 33 degrees coupled with a hip extension of 11 degrees. In hip flexion, he demonstrated a maximum of 27 degrees.

NA2 is a 33 year old male, 5'9", 182lbs (82.72kg) with an athletic build. NA2's first 50 meter swim was at 12:15 pm. His starting blood pressure was 156/91 (Stage One) and starting heart rate was 105 bpm. He accomplished this task in 65 seconds without the use of his arms at a speed of 0.769 mps or 1.720 mph and by burning a total of 10.45 calories. His final blood pressure was recorded at 149/87 (Stage One) and ending heart rate was 115 bpm. Looking at NA2's swim technique, he has a maximum knee flexion of 55 degrees coupled with a hip extension of 12 degrees. In hip flexion, he demonstrated a maximum of 31 degrees.

NA3 is a 44 year old female, 5'7", 164lbs (74.54kg). NA3's first 50 meter swim was at 12:30 pm. Her starting blood pressure was 130/85 (Prehypertension) and starting heart rate was 102 bpm. She accomplished this task in 62 seconds without the use of her arms at a speed of 0.806 mps or 1.802 mph and by burning a total of 8.99 calories. Her final blood pressure was recorded at 118/83 (Stage Two) and ending heart rate was 136 bpm. Looking at NA3's swim technique, she has a maximum knee flexion of 42 degrees coupled with a hip extension of 9 degrees. In hip flexion, he demonstrated a maximum of 33 degrees.

Comparing the three non-amputees, all three performed the task in less than 65 seconds. Their angles give us a small pool of averages to compare our amputees to. For instance, knee flexion angles fall between 33-55 degrees. The hip extension angles fall between 9-12 degrees. While the hip flexion angles fall between 27-33 degrees. For knee flexion, all transtibial amputees fell in and around this range but the main concern is that these are not symmetrical between limbs in each subject. The transfemoral fell very short of the range on the prosthetic side and completely passed the range on the sound side. In hip extension, the unilateral transtibial amputees fall into the range and the bilateral transtibial amputees overshoot it. UAK1 exceeded it only on the sound side by about 20 degrees. Lastly, on hip flexion, our unilateral transtibial amputees were quite different and this will attribute again to the level of intensity during the trials. UBK1 exhibited very small hip flexion values with his smaller kicks and UBK2 fell right into the range. Both bilateral transtibial amputees were considerably less since their hip extensions came out so high. UAK1 fell into the ranges and did so very symmetrical. Spread was only measured on the bilateral transtibial amputees and the non-amputees but in the chart (Fig. A15-2) you can see a large increase in the spread to these bilateral subjects.

Subject	Knee Flexion	Hip Extension	Hip Flexion	Spread
UBK1	63°S - 42°P	3°S - 5°P	2°S - 8°P	N/A
UBK2	52°S - 41°P	9°S - 4°P	28°S - 24°P	N/A
BBK1	36°	26°	11°	49°
BBK2	28°	28°	12°	50°
UAK1	70°S - 7°P	32°S - 9°P	26°S - 31°P	N/A
NA1	33°	11°	27°	30°
NA2	55°	12°	31°	36°
NA3	42°	9°	33°	29°
S=Sound Side P=Prosthetic Side (All ROM are maximum recorded)				

Fig. A15-2

Another measurement that was not included in all the studies and only collected from NA2 is the range of PF during his swim. His maximum PF was recorded at 80 degrees and minimum at 12 degrees. This is a 68 degree ROM that is needed during a typical swim pattern. Granted this is only one swimmers range but it shows the option we have as non-amputees. All amputees in this study wore a prosthetic foot with a fixed 70 degrees and this is fixed at all times throughout the swim. This gives them an advantage while kicking down but resistance on kicking up. This makes the prosthetic swim foot another key area to focus on when trying to find new ways to improve speed and energy efficiency.

SPLIT FIN SIDE STUDY

In this study we had Oceanic show us a Split Fin design that we also wanted to try. They were the Oceanic V-16 Open Heel Split Fin with Rubber Heel Straps (14.4131) (Fig. A16).

Fig. A16

This fin is meant to be used with a flutter kick. Instead of larger and slower kicks, you do small faster kicks. This is important here because you do not create as much torque because the water passes through the fin. This means that the ROM needed for split fins is significantly less. We had three amputees conduct the 50 meter trial with the split fins. This was their first time ever trying this style of fin. The final statistics can also be seen on the attached spreadsheet (SA2013) along with all the other trials.

UBK1 was the first to try the split fins. He finished the 50 meters in 68 seconds which is 1 second faster than with regular fins. He burned fewer calories with the split fins and was therefore more energy efficient. His blood pressure stayed in the same category where as in the regular fins, it jumped up one. His heart rate was lower and he also reported that it seemed easier.

UBK2 also reported that it was much easier and with his already “more than casual” speed, the flutter-kick shaved another 2 seconds off his time. In his first trial with regular fins, UBK2 jumped up a category in blood pressure and interestingly with split fins, he dropped a category. His heart rate stayed the same during the two trials but overall he was more energy efficient with the split fins. This makes sense in the trials with the unilateral amputees because they were constantly over-compensating the sound limb to get a big kick and with the flutter-kick demanding a much smaller spread, the trimlines and sleeves do not hinder them near as much. The ROM required is overall less with the split fins.

UAK1 was the last person to try the split fins. His results were not as clear as our transtibial amputees. He was one second slower and his vitals were nearly all identical when using split fins. UAK1 felt more comfortable with the split fins and again this might be because of the decreased ROM required and the decreased torque on his residual limb. He did not have to fight for maximum hip extension because it was simply not needed. UAK1 chose to continue using the split fins on a 100 foot dive later that day.

In this added case study, the split fins seem to work very well and helped the amputees become more energy efficient and decrease the torque on their residual limbs. A larger pool of subjects will be needed to help prove this theory.

PROSTHETIC NEEDS

This case study has brought several needs to our attention. A few have already been mentioned but let's start from the foot up. Prosthetic feet have come a long way in the advancements on land. However, there have only been a couple styles available for swimming and both have been adequate at getting amputees into the water. However, we have far to go. As mentioned earlier, our feet go through a range of motion during normal swimming and locking our feet in at 70 degrees of PF is not optimal. We need a foot that can adjust in real time to our kicking style. The ability to lock it at neutral for ambulation outside of the pool or ocean is great and this would continue to be needed. In mentioning the switch on the foot that allows the amputee to lock it into Neutral or 70 degrees of PF, it was very obvious that this was not very easy to do for all amputees. At the pool, sure you can sit on the side and PF your foot before swimming. However, while in the water, trying to reach all the way down to your ankle to get it back to neutral did not come easy to these very athletic gentlemen. Especially in the ocean, the waves are hitting you and knocking you around before you step onto the ladder of the boat and all your trying to do is dorsiflex your foot. The roll entry was best suited for getting into the water as the amputees could PF their foot on the boat and roll backwards into the water. If we could move this switch from the ankle more proximal and perhaps onto the side of the socket, it would make this action much simpler to accomplish.

Suspension would be next and primarily because of the buoyancy issues. Suction and vacuum seem to both work great. No one's prosthesis ever came off during a trial and these men certainly put it to the test. It is the amount of air and weight we keep in the prosthesis itself that will ultimately control how buoyant it is. If it is vacuum that we choose as our suspension, it might be necessary to offset its weight with high density foam to help move through the water and not have to fight to keep yourself at the surface. The second idea of having a buoyancy control unit on the prosthesis itself would be a great addition to the diver who wishes to go to greater depths ascending and descending.

Moving on to the knee and to our transfemoral amputees, we need a prosthetic knee that can give us the flexion we need and return to full extension during the swim cycle. This will level out our transfemoral amputees, give them more propulsion, and take less energy. If we can get the X3 to the depth we need, this can possibly become a reality in our next study.

Our socket adjustments are also going to be key. The trimlines, and specifically our posterior proximal trimlines, need to come down and give our amputees more ROM. The fit of the socket is also critical. Torque was mentioned earlier and the effects it can have on the residual limb. The more ply an amputee has to wear the more room he has in his socket. A great fitting socket with total contact will increase proprioception in the water and create less torque. The other option that is possible, and more for our bilateral amputees, is directly attaching the fin to the end of the socket. This eliminates your long lever arm and therefore the amount of torque on the limb. This was not tried in this study but there have been other amputees that have mentioned it being a benefit. Sampling this type of prosthesis and comparing it to our baseline measurements we have collected here could prove it right or wrong.

<u>VARIABLE CONSIDERATIONS</u>

In future time trials, there are some notable considerations that will be avoided. One is the use of arms during the trials. It is understandable that the amputees will need to use their arms for propulsion underwater when not using their prosthesis or prostheses. However, it will be beneficial to have them use their arms also while using their prosthetics. This will help limit the variable between the two studies.

Another consideration would be the use of fins. The subjects in this study used fins with their prosthetics and did not use fins when they took their prosthesis off. The unilateral amputees are the main consideration here. What if they wore a fin on the sound leg? Would this show a benefit in energy efficiency or just a deviation in swim technique? This is one variable to correct when conducting another study.

A third consideration would be to have the amputees swim without scuba equipment. How does scuba equipment help or hurt our technique. In most situations, it helps us maintain buoyancy but in technique it is a mystery. A future study will look at the amputee swimming on top of the water with no scuba equipment, a snorkel, and the ability to use their arms on both trials. This will also correlate better to the uncertified amputee in a more everyday setting.

The fourth variable comes in experience. Most of these gentlemen are very accustomed to the water. In fact all of them combined together have over sixty-four years of certified diving experience. This gives them an edge in swimming with dive gear, adjusting buoyancy, and using fins. Granted not all of those years they were using a prosthesis or prostheses but it is still a benefit. Again, with new trials next year conducted on top of the water, we can eliminate some of these variables. With all the collected information and foresights on future studies, it might be advantageous to split the study into a diving only and a swimming only case study.

The final variable is the term that was given to these subjects the day of the study when asked how fast to swim. The term is the word, “casual”. It can be understood in different ways and on a scale of one to ten; everyone will give it a different number. Therefore, all amputees and non amputees in this study swam at their own defined term of “casual”. If we want a true baseline of where our prosthetics are now, we will need them to swim at their fastest pace and therefore will eliminate any comprehension of the term. This will also help in comparing and contrasting the same amputation types when the stress levels are similar.

In closing, the goal of this case study was to create a baseline of information for amputees swimming a predetermined distance. With several variables accompanying it, we accomplished that. All the data recorded in this case study and on the attached spreadsheet (SA2013) can now be used to compare to future studies. With a growing pool of subjects we can begin to identify the typical swimming pattern of all types of amputees and all types of prostheses. The facts and visualizations learned here will help us design and fabricate new types of sockets, knees, suspensions, and feet for the prosthetic swim world. Along with scuba manufacturers such as, Oceanic, we can also create adaptive scuba equipment to aid in the advancement and enjoyment for all amputees worldwide. The next case study and research project scheduled in July of 2014 will help grow this statistic database

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