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Concept Designs for Underwater Swimming Exoskeletons

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***Abstract*— We present several biologically inspired concept designs and feasibility analyses for underwater swimming exoskeletons. These designs are biologically inspired, based on observations of dolphins, sea turtles, and penguins. Biologically inspired designs have the advantages of stealth, maneuverability, and a natural interface when compared to propeller driven underwater propulsion devices.**

We present a lower body concept, based on dolphin locomotion and an upper body concept based on sea turtle and penguin locomotion. The dolphin based concept has the advantages of using the wearer's most powerful muscle groups, of being the most natural to swim with, and of leaving the user's hands free for other tasks. The sea-turtle based concept has the advantage of novelty and may have appeal as a recreational device.

We predict that with actuation and energy storage components available today, an exoskeleton that produces a cruising speed of over 1 m/s and a top speed of over 1.5 m/s is feasible. We estimate that cruising at 1 m/s can be achieved with less than 504 Watts power consumption, which translates into 2.4 kg of off-the-shelf silver-zinc batteries per hour of operation.

Keywords- exoskeleton; robotics; underwater swimming; human

I. Introduction

A human in water is like a fish out of water. We swim slowly, maneuver poorly, have high-drag bodies, and can only stay underneath the surface for mere minutes before dying. Humans have compensated for these deficiencies with the inventions of fins and SCUBA equipment, but our capabilities still pale in comparison to our piscine and cetacean brethren. While the top speed for a human diver equipped with fins is approximately 1.5 m/s [1], dolphins are known to achieve a maximum speed of 10 m/s [2]. For extended periods, a human diver can cruise at a speed of approximately 0.5 m/s, whereas a dolphin can sustain speeds of 2.8 m/s [2].

With advances in robotics and exoskeleton technologies, it is now feasible to augment human divers' capabilities in such a way that they not only swim on par with dolphins but *feel* as though they are a dolphin. This sensation is achievable through amplification of the human's motions and forces through an exoskeleton swimming suit. Such an exoskeleton has a natural interface, in fact lacking any obvious interface, such as a throttle or steering mechanism, which exists with traditional propulsion devices. With no interface to master, there is potentially less instruction required and a decreased cognitive load on the user, allowing them to use their mind for other tasks.

There currently exist several types of machines that can propel or transport a human underwater. These devices include small submarines and personal propulsion crafts, like the Sea-Doo Seascooter [3]. Compared to these technologies, biologically based exoskeletons have several advantages:

- Stealth. An exoskeleton's audible signature may be indistinguishable from ecological background noise. In contrast, propeller driven devices generate a loud distinguishable noise due to propeller cavitation.
- Natural Interface. An exoskeleton is operated naturally. In order to swim, the user simply performs a swimming motion. In order to speed up, the user speeds up the swimming motion. A well designed device will directly amplify, without impeding, the user's natural motions so that it truly is an extension of the wearer's body.
- Hands-free Operation. A lower body exoskeleton can be operated based solely on the motion of the wearer's lower body. This leaves the wearer's hands free for other tasks.

Significant research has been conducted on exoskeletons that augment a human's capabilities in land-based settings. These exoskeletons have been designed for increasing strength and endurance of the human. Kazerooni [4] details a design that interfaces with the upper body of a human and allows a person to lift and move extremely heavy loads with only a fraction of the actual required force. Devices that interface

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with the lower extremities will allow a person to effortless carry heavy loads for long periods of time [5],[6]. Although there are existing technologies to transport heavy loads, an exoskeleton offers a natural and ergonomic interface with the human, making the exoskeleton feel like an extension of the user's body.

This paper examines biological underwater swimmers for inspiration and presents some concepts for swimming exoskeletons.

II. Biological Inspiration

Underwater animals provide design inspiration because evolution has already provided sucessful designs. The range and type of motion that can be produced by joints, muscle, and tendons is common to both humans and many other animals. Additionally, the turning radius, turning rate, and stealth of biological systems often exceed those of engineered systems [7].

For our purposes, we can divide biological swimming propulsion into two types: body and/or caudal fin (BCF) locomotion and median and/or paired fin (MPF) locomotion [8]. The BCF locomotion involves a body wave that starts at the front of the body and moves to the tail. Between different animals there exists a continuum of where the body wave starts; at one end of the spectrum is anguilliform, in which a wave travels down the entire body, causing it to undulate. At the other end of the spectrum is ostraciiform, in which only the tail section oscillates, or pivots relative to the body.

As with BCF locomotion, MPF locomotion has a spectrum of motions. At one end is rajiform, seen in fish such as rays, skates, and mantas, which use an undulation motion. At the other end is labriform mode, in which propulsion is achieved by oscillatory movements of the fin. Within labriform mode, there are two types of movements, drag-based, or rowing, and lift-based or flapping motion [9]. The drag-based mode is where a large area is presented parallel to the flow, and moved through the fluid in the opposite direction of the desired movement, resulting in forward thrust. With the drag-based mode, the oscillation of the fin can be divided into two phases, the power stroke, which produces thrust, and the recovery stoke, which returns the fin back to the start of the phase. For lift-based mode, the fin or wing is moved generally perpendicular to the forward motion, creating a lift, or thrust, force, to propel the body. In the lift-based mode, thrust can be obtained from both the up and down stroke. Lift-based propulsion is used by penguins and sea turtles. Often, swimmers will use both drag- and lift-based modes, depending on the speed at which they are moving. The drag-based mode is more effective at low speeds and the lift-based mode is more effective at high speeds [10].

III. Concept Deisgns

The two types of fish locomotion suggest two different types of augmentation schemes for a swimming exoskeleton. The first type, based on BCF locomotion, provides an augmentation to the lower extremities. The second type, based on labriform, a form of MPF locomotion, provides an augmentation to the upper extremities. A swimming exoskeleton device could consist of either or both types of augmentation.

A. Lower Extremity Augmentation

The strength of humans swimming underwater with fins comes primarily from the lower extremities. Swimming fins easily provide a simple boost in speed and efficiency. Use of the legs in underwater swimming can most commonly take on two forms. One form is similar to anguilliform, and is called the dolphin kick. The other form, which is most like ostraciiform swimming but with the legs moving separately and out of phase, is called the flutter kick.

Several variables are crucial to an optimal architecture of an exoskeleton. At issue are the number of joints, type of joint, and whether the joints are active, passive, or fixed joints. In addition, any design must be constrained by the human's major degrees of freedom at the hip, knee, and ankle. For both types of swimming form, the motion of the body is in the vertical plane, but for comfort and maneuverability, out of plane motions, most likely passive, will be necessary. The requirement for actuating a joint depends, in part, on the design purpose of the exoskeleton. If designed for reducing effort, then some of the degrees of freedom which require modulation, but are low power, can stay unpowered and actuated only by the human. If designed for increased speed, the resulting increased forces required at joints that are un-powered might exceed what the human can provide. A concept drawing of a potential design for a lower extremity exoskeleton is shown in Figures 1 and 2.

From studying video of human underwater fin swimming, it appears that the ankle joint is typically passive. For the freestyle kick, on the downward stroke, the ankle is flexed to its maximum point. During the upstroke, the ankle is passively positioned so that the fin experiences the least amount of resistance through the water. Therefore the ankle joint might not need actuation. It might, however, require some type of mechanical rotational joint with a limit on the amount of rotation. This joint would transfer the load to the lower leg during the down stroke instead of requiring the ankle to transmit the entire load.

Further study of fin swimming reveals that most of the thrust is obtained during the down stroke, or the power stroke, which is confirmed by Pendergast et al. [11]. As a first approximation, the amount of thrust can be related to the amount of deflection in the fin. During the down stroke, the fin is flexed, indicating the presence of a thrust force between the water and fin (Figure 3). During the up stroke, or recovery stroke, the fin is almost flat, indicating little force between the fin and the water. To mimic a human with fins, therefore, actuation might only be needed in one direction.

Figure 1 Concept drawing of lower extremity exoskeleton, front view. Rotary motors are shown actuating the knee joint and hip joint.

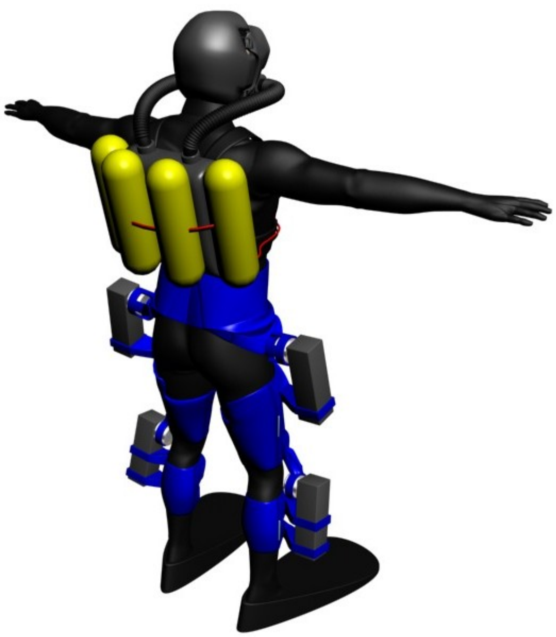

Figure 2 Concept drawing of lower extremity exoskeleton, rear view. Yellow cylinders on the user's back are battery supply. Diver shown with rebreather.

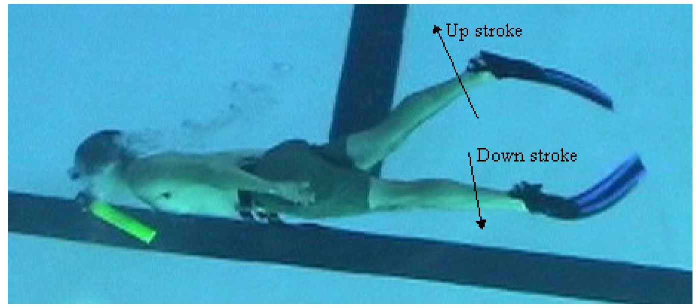

Figure 3 Underwater fin swimming. Thrust is generated mainly by the down stroke as indicated by the curvature of the down stroke fin.

The need for actuation in only one direction can possibly simplify the actuation needs. However, the reason for the imbalance of thrust production is due to the anatomical joints and muscle power ratio of a human; the quadriceps are generally stronger than the hamstring muscles. The use of an exoskeleton can overcome these physical limitations of the human body. Most piscine BCF swimmers have a symmetrical stoke, getting thrust from both halves of the cycle. Therefore, actuators augmenting both the up and down stoke can ultimately result in more efficient swimming. However, dolphins obtain most of their propulsive thrust from the downstroke [12]. Only through prototype testing will the most efficient architecture be determined.

B. Upper Extremity Augmentation

Underwater swimming by means of the upper extremities, the arms, is not a very natural means of propulsion for humans. In order for underwater arm swimming to be efficient, some form of end effector is needed. In labriform mode, the exoskeleton design must include such end effectors.

The current research in hydrodynamics of biological systems forms a basis for the design of a lift-based fin. The propulsive capabilities of a flapping foil has been experimentally verified [13], showing efficiencies of up to 87%. In flapping foil propulsion, the relationship between the angle of attack and the transverse motion significantly affects the propulsion efficiency. When considering flapping as a means of propulsion, a continuously variable degree of freedom for the pitch of the foil is required. The efficiency of the flapping foil can be further increased by adding chordwise flexibility [14]. By manufacturing the foil out of a flexible material, for example urethane rubber, an increase in propulsive efficiency can be achieved. Such biologically inspired propulsion methods are increasingly evident in the designs of underwater vehicles [15],[16].

Figure 4 Concept drawing of upper extremity exoskeleton, front view.

Figure 5 Concept drawing of upper extremity exoskeleton, rear view.

A concept design for an upper extremity exoskeleton is shown in Figures 4 and 5. For an exoskeleton to allow a human to swim in the labriform mode, the human would perform the flapping motion and the robotic device would interpret these motions through force sensors and amplify the output force. Because the required torque on the pitching motion would be relatively small, this degree of freedom could remain passive. The force augmentation would occur on the flapping motion itself.

Despite the utilization of flapping propulsion in robotic vehicles, the application of flapping propulsion to human swimming does not seem as practical. The major drawback to upper extremity design is that the flapping motion is not a natural form of swimming for humans. Even though the robotic device would provide most of the force required for locomotion, the user would still be required to perform the basic motion. The other difficulty with an upper extremity exoskeleton is having the user control the pitch of the fin. For aquatic animals, the control of the pitch is performed through sensory information about the flow and pressure over the fin. This information can determine if the angle of attack is too great, and the flow is near or at stall. In the case of an exoskeleton, a method for sensing this information and projecting it to the user would be required. Despite these drawbacks, there is still value to designing and testing an upper extremity exoskeleton. Aside from its novelty, such a device can aid in the design of a flapping foil swimming robot.

IV. Actuator and Energy Source Selection

An ideal exoskeleton will have a natural, intuitive interface, and feel like an extension of the user's body. For a terrestrial exoskeleton, this requires very low impedance actuators. For a marine exoskeleton, the user always feels a drag force from the water; therefore, moderate impedance may be tolerable. A small additional force from the device may be imperceptible when compared to the impedance caused by the water, and thus will not interfere with the user's natural motions.

There is a range of actuators that have previously been used in exoskeleton design. One type is the McKibben Muscle [17]. This type of actuator is attractive for its simplicity. In addition, the inherent compliance offers desirable impedance characteristics. Another type is a traditional fluid, either hydraulic or pneumatic, actuator. This type also has similar advantages as the McKibben Muscle. Series Elastic Actuators are a proven method of providing force amplification while still giving the user natural movement [18]. With Series Elastic Actuators, a spring is placed in series with the actuator and a force measuring component so that the user's intent is properly monitored and converted to the appropriate force. Series Elastic Actuators are electric motor driven actuators, available in linear or rotary form. In terms of force control, the Series Elastic Actuator offers the higher bandwidth and more precise force control compared to fluid and McKibben actuators. New actuator technologies, like electroactive polymers [19] are still only practical for small amounts of force generation.

Options for underwater energy storage include electrical batteries, pneumatic tanks, hydrogen fuel cells, and closed-cycle diesel combustion. Silver-zinc electrical batteries offer sufficient volumetric and weight energy densities. Additionally, the stored energy is in a very useful form if electrical actuators are used. Compressed air, while being light, offers poor volumetric energy density in comparison to electrical batteries. Fuel cells have similar energy densities compared to batteries when their oxygen cannot be obtain from the atmosphere. Closed-cycle diesel requires significant additional hardware to eliminate the need for fresh air. Silver-zinc and Lithium Ion batteries appear the most practical for initial prototypes.

V. Power and Energy Analysis

Our initial estimates of energy requirements for the exoskeleton indicate that the needs can be met with current energy storage technology. The power requirements for underwater fin swimming are difficult to measure because the drag on the body changes during the course of the kicking motion. The estimated energy requirements are made under the assumption that the exoskeleton does all the work, unassisted by the human. In operation, the human will provide some of the power required for propulsion. Once the exoskeleton is designed, an area of study will be the determination of the proper amount of augmentation for each actuated joint.

We examine four different methods of determining the drag force because the results vary quite considerably due to much inherent uncertainty. All four estimates result in the conclusion that the device is feasible with the current technology. The results are summarized in Table 1.

Method 1, Passive Drag: This method estimates the power requirements based on the power required to tow a person, without gear, underwater. Lyttle et al. [20] towed 40 individuals underwater at a depth of 0.6m. They estimated the passive "drag coefficient", which is actually a viscous damping coefficient, to be 22.5 $N/(m/s)^2$. At 1.0 m/s, the passive drag would be 22.5 N, and the mechanical power required to overcome the drag would be 22.5 Watts. At 1.5 m/s, the passive drag would be approximately 50 N and mechanical power 75 Watts. This gives us an absolute lower bound on the mechanical power required to move a person through the water, assuming we do not reduce their drag.

Method 2, Active Drag: For the exoskeleton power calculations, the drag while actively kicking (active drag), is more appropriate than passive drag. A technique for measuring active drag is described by di Prampro et al. [21]. They estimated that the active drag for surface swimming of 10 subjects at two different speeds was an average of 94.3 $N/(m/s)^2$. With this drag coefficient, at 1.0 m/s, drag would be 94.3 N and mechanical power 94.3 Watts. At 1.5 m/s, drag would be 212 N and mechanical power 318 Watts. Pendergast et al. [22] report that the drag at the surface is greater than the drag underwater, which would reduce these power estimates. However, these estimates are for divers with no gear and therefore do not include the required diving gear with its resulting added drag.

Method 3, Maximum Thrust: This method estimates the required power requirements based on the maximum thrust force that a fin swimming human can produce while tethered in stationary water. Pendergast et al. [23] determined this maximum thrust force as an average of 146 N, which only can be sustained for short periods as it is generated through anaerobic activity. We assume that maximum thrust force is the upper bound on the maximum drag force that an underwater diver would experience while swimming at full speed, which is approximately 1.5 m/s. To be conservative, we will assume that the same drag force is present at the 1.0 m/s speed as well. The resulting power requirements are 150 Watts of mechanical output power at 1.0 m/s and 225 Watts at 1.5 m/s.

Method 4, Metabolic Energy Expenditure: This method estimates the required energy based on the energy that a human expends. Human oxygen consumption for fin swimming at 1 m/s is about 3.5 liters/min [23], which converts to 1200 Watts of metabolic power. Part of the energy that the swimming person is consuming, however, is going to heat generation as well as baseline functions. Assuming a muscle efficiency of 25% (the maximum measured when performing positive work), we get 300 Watts of internal mechanical power at 1.0 m/s. We can estimate the power required to swim at 1.5 m/s, which is the top sprint speed for a human by looking at the peak mechanical work output of a human [1]. Bar-Cohn et al. determined that well trained humans can maintain 1200 Watts of mechanical work for a few minutes [24]. Assuming that these two activities have equivalent power outputs, we can estimate an internal mechanical power output of 1200 Watts is required to maintain a speed of 1.5m/s. Therefore, we arrive at estimates of 300 Watts and 1200 Watts of internal mechanical power to achieve speeds of 1.0 m/s and 1.5 m/s respectively.

Prempraneerach et al. [14] have shown that pitching and heaving foils can achieve propulsive efficiencies over 70%. Pendergast et al. [23] have shown that divers swimming underwater with fins achieve propulsive efficiencies of 60-72%. Zamparo et al. [25] have shown that surface swimmers with fins achieve propulsive efficiencies of 70%. Therefore, in converting from output power to internal mechanical work, we will assume that the robotic device is providing all the power, with a propulsive efficiency of 60%. We will assume in converting from internal mechanical power to electrical power that we can achieve an efficiency of 70%. These estimates are listed in Table 1. We see that we have an upper bound of 504 Watts of electrical power at 1.0 m/s and 1714 Watts at 1.5 m/s. These are conservative upper bounds and assume that the device will do all of the work, with zero assistance from the user.

Using silver-zinc batteries having an energy density of 750,000 J/kg or 4.8 kg/kWhr [26], the resulting weight will be less than 2.4 kg per hour at 1.0 m/s and 8.2 kg per hour at 1.5 m/s. For six hours of operation at 1.0 m/s, this results in 14.4 kg. Silver-Zinc batteries have a density of 0.5 L/kg (specific gravity of 2.0). Thus the six hours of operation would require 7.2 Liters of battery, which is approximately half the size of a medium SCUBA tank.

VI. Discussion

Underwater swimming exoskeletons are feasible. We describe two different designs, an upper extremity enhancer and a lower extremity enhancer. The more practical design is the lower extremity enhancer. For the lower extremity design, the critical issue will be the number of degrees of freedom and which of them to power. We predict that with actuation and energy storage components available today, an exoskeleton that produces a cruising speed of over 1 m/s and a top speed of over 1.5 m/s is feasible. We estimate that cruising at 1 m/s can be achieved with less than 504 Watts power consumption, which translates into 2.4 kg of off-the-shelf silver-zinc batteries per hour of operation.

Because robotic exoskeletons, by definition, involve the dynamics of the person, simulating the system is extremely difficult. The architecture of the device can only be determined through prototype testing of various configurations. In the next phase of this research, we will test what types of joints are required at the hip and knee and will build a prototype.

TABLE 1 *REQUIRED POWER ESTIMATES.*

Required power estimates using four different methods at two speeds: 1.0 m/s is cruising speed, and 1.5 m/s is sprint speed. Output power refers to the power required to overcome drag. The internal mechanical power refers to the power required at the actuators, which includes the active drag, the power transferred to kinetic energy of the water, and internal motion. For our analysis, the internal mechanical power was calculated as the output power divided by the propulsive efficiency, which was assumed to be 60%. The electrical power was calculated as the output power divided by the actuator efficiency, which was assumed to be 70%.

Method	**Speed** (m/s)	**Output power** (W)	**Internal mechanical power** (W)	**Electrical power** (W)
Passive drag	1.0	23	38	54
	1.5	75	125	180
Active drag	1.0	212	353	504
	1.5	318	530	760
Max thrust	1.0	150	250	357
	1.5	225	375	535
Oxygen consumption	1.0	N/A	300	428
	1.5	N/A	1200	1714

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