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Power and Endurance for Comfortable Wearable Robotics

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Abstract— **The augmentation of human power and endurance by way of a power assisted exoskeleton could revolutionize rehabilitation, industry and the battlefield. The use of servo motors placed near limb joints results in a rotary motion of the human limb which adapts well to attaching the exoskeleton to the limb and to integrate limb movement. Air muscles or pneumatics offers advantages over DC motors for instantaneous high thrust limb motion using light weight components and even soft and malleable exoskeletons. However these implementations mimic human muscle and apply forces longitudinally resulting in high compression forces on the longitudinal exoskeleton. In the rotary approach forces are applied perpendicularly so as to flex adjoining limbs. In this rotary case the device can be designed to be more easily attached and worn. The work reported here describes the progress with a new type of exoskeleton and air muscle design based on a new approach to exoskeleton and air muscle layout that combines contractive actuation with rotary motion. The aim is to reduce the need for bulky exoskeleton members, share out forces over larger areas and thereby demonstrate strapless, comfortable and easy fitting footwear. The developed prototype is tested for augmenting a test subject's explosive power and significantly reducing the metabolic cost of walking while carrying a heavy load.**

I. Introduction

SEVERAL exoskeleton robotic devices have been demonstrated both by commercial and academic researchers. The now commercially available devices [1] to [5] are available for rehabilitation and some quasi-military applications. These have been based on earlier academic research such as [7-11].

The designs have several distinguishing features that contribute to both the advantages and the disadvantages of each approach. These features include the drive method, the skeleton, the mode of operation and the integration of the human user's needs.

For example the drive method for [1-3] is based primarily on electric servo motors mounted near the human limb joints. These servos act to rotate the exoskeleton near the joints and rotate the limbs by driving forces acting perpendicular to the human bone.

Whereas [4-6] are based on pneumatics or air muscle, in which case the drive method is a contraction force which pulls the limb or exoskeleton around a joint or pivot point. These two approaches result in different exoskeleton requirements.

Contractive drives based on light weight fluid or air pneumatics can be designed to act at the point where forces are needed and result in light additions to the human limb. The heavier power generating apparatus, such as a compressor, can be placed at a more convenient remote region.

Rotary mechanisms place the direct drive, heavy servo motors near the limb joints adding substantial weight to the human limb and the servo motors need strong structures to support them. Therefore, only systems, such as the XOS suit from Raytheon Sarcos [1], with a substantial exoskeleton, can carry heavy but powerful motors near the limb joints so as to provide the high levels of forces that expand the human capability. In contrast the HAL Suit [2], with smaller light weight servo motors can be designed into a more elegant and comfortable suit however this system cannot provide as powerful power assistive forces.

Relocated drive systems have been designed based on Bowden cables [7]. However these can suffer from frictional losses and the cable support infrastructure adds to the overall weight.

Contractive drives can act almost instantly delivering very high thrust and can be used to assist sudden actions such as jumping or jerking. Servo motors that can deliver high instantaneous torque are inherently heavy and their placement at limb joints contributes to the strength to weight problem, restricting the desired sudden limb action.

However contractive drives have two major disadvantages over rotary drives. First contractive drives require two anchor points for each simulated muscle. This complicates the exoskeleton design raising design issues around whether these anchor points should be directly mapped to the human body or to some supporting exoskeleton. When attached to the human body, anchor points based on straps and adhesives are

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very uncomfortable and only limited forces may be produced before the person is hurt. Secondly the contractive drive works by creating a longitudinal pressure across the limb joint connecting the two attached limbs. This pressure leads to a collapse in the relative angle between the limbs. To provide robotic power augmentation, a wearable device must add even more pressure on the human limb joint, something the human would not necessarily like or be able to withstand. Therefore, soft suits have limitations, and contractive drives need eventually to use hard exoskeletons for high power applications.

In theory there is no difference to the observed movement involved when using a contractive or rotary drive to rotate two structures hinged at a pivot point.

However in practice when a payload such as a human's limbs need to be carried and moved by the hinged structure, the most comfortable arrangement appears to be when the resulting contact forces between the structure and the human limb are distributed across a larger surface and not at one point.

The principle is similar to that of the kneeling chair [13], with which one can share out body weight between the buttocks and the shin area or any human harness or seating saddle. Better displacement of forces tends to result in a more comfortable feeling and the human can integrate it into their actions rather than resist its discomfort.

Rotary drives accomplish this by generating forces perpendicular to payload limbs. Contractive drives generate forces parallel to the limbs which are then indirectly converted into comfortable rotation like forces.

So although contractive drives are attractive for their power and low weight, a new approach is needed to apply them in a comfortable and high power manner. This is the key point of the research work presented here.

Exoskeletons fall into what could be described as hard or soft categories. A hard exoskeleton, of which the XOS suit is an example, provides a great deal of mechanical support, providing load bearing structures for the limbs, the motors and the payload. The main problem with these types of hard suit is that they impede the normal gait of the user as they cannot mimic the multiple degrees of freedom of the human body that it encapsulates [14].

On the other hand soft suits have been proposed which essentially replace the hard exoskeleton with a variety of straps that hug the body. These straps blend with the body motion however they inherently displace forces to parts of the body which are not related, for example the hip is a primary anchor point even for muscle action around the calf muscle. For example in [6] the exosuit is designed to provide only 50% assistive force and this was not achieved fully due to compliance. Although the soft suits have much less impact on natural gait, their role in high power assistive devices would appear to be limited.

Up till now it would appear that if the objective is to significantly augment a human's strength, then a hard exoskeleton is mandatory and this brings with it the problems mentioned. However in this research we hope to change this design approach by proposing an alternative approach that blends comfort with high forces.

The final aspect that differentiates ongoing research in this field is the manner in which the design integrates the robotic aid with human motion. Some advances have been made in the integration of the intent of the user, by monitoring either the muscle driving nerves or the users brain, in order to determine when to drive the motor or pneumatics of the assistive device [10],[15].

The overall aim of our work is to develop an exoskeleton and drive system which can reduce the metabolic cost of walking significantly while carrying a heavy load. An additional aim is to achieve this without impacting the comfort of the user because of soft suit straps and adhesives or degrading the gait of the user with a hard encapsulating frame. In addition the design should lend itself to working synergistically with the user so that the user takes advantage of the robot, rather than directly controls it.

This paper comprises section II describing the proposed new approach to exoskeleton design and actuation and how it may be used for different limb assistance problems. Section III describes Hubot, a lower leg assistive prototype built to test the concept. Section IV presents the tests performed to determine the effectiveness of the design approach and discusses the results of the test performed.

II. Principle of Operation

The human body typically has limbs as shown diagrammatically in figure 1a and 1b.

A lower leg limb may be simplistically modeled as a skeletal bone support and calf muscle and shin muscle. The foot comprises a joint and ball of foot and a further set of joints towards the toes. The muscles are adhered to the skeleton by tendons and cartilage. The human movement of the foot is caused by the muscles 5 or 6 contracting and relaxing, pivoting the foot 2 around the joint 3.

Similarly the torso 8 has hip joint 9 and lower thigh skeletal bone 10, with muscles groups adhering to the bone. The thigh is rotated by antagonistic action of the muscle groups 11 and 12.

In mimicking the human biology traditional approaches to robotic assistive devices using contractive drives have relied upon the creation of a hard exoskeleton or a softer net of straps envelope the limbs and body providing sufficient structure that muscle like actuators may bring about forces to move the limbs.

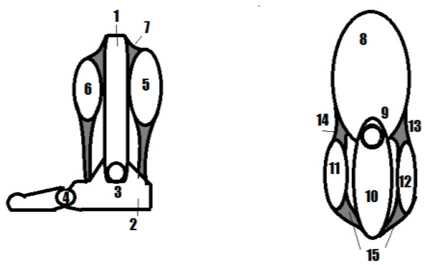

Fig. 1. Figure 1a on the left shows a simple model of the human lower leg bone and muscles, 1b on the right shows the upper thigh jointed to the torso with primary thigh muscles.

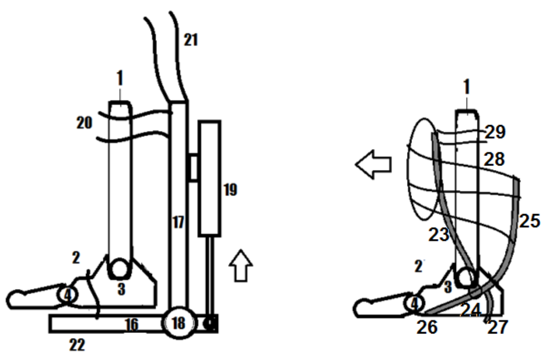

Fig. 2. Figure 2 a on the left shows a simple model of a traditional contractively driven exoskeleton, figure 2b on the right shows the layout of the exoskeleton proposed in this new research work.

A traditional approach is depicted in figure 2a. In order to drive with very high forces, one cannot use a soft suit as the straps and adhesives applied to the skin can cause discomfort, so a "hard" support member 17 must be introduced. The exoskeleton consists of a base plate and a hinged vertical support where actuator 19 can cause the base plate 16 to rotate around 18 by pulling the attached rod vertically upwards. The strap 20 has two important roles. Its first role is to keep the structure 17 adhered to the limb so the exoskeleton and contractive drive cannot flop around. The second role is to transfer the actuation forces of 19 into pressure forces on the front of the shin so that the shinbone, 1, is rotated about the ankle, 3.

It is our opinion that this approach, as used by Ferris [8], results in a less comfortable, less wearable and less fashionable solution.

In the approach researched and presented here the traditional arrangement of hard exoskeleton is replaced with a slightly modified one as depicted in figure 2b.

In this design a padded curved saddle and rod 23 lies comfortably against the front of the shin and its lower end joins at 24 to the second curved rod 25. Rod 25's lower end meets the ground at 26. A strap 27 attaches to rod 25 and passes under the ball of the foot and adjoins the other fork end of 25. Rod 23 has attached an inflatable pneumatics that when inflated pulls on the ties 28 which causes rod 25 to rotate about 24. This causes the lower end of rod 25 to drive into the ground. The strap connected to rod 25 pulls the ball of the foot upwards, causing the foot to rotate about 3.

When the pneumatic muscle expands the padded saddle and rod 23 is pushed against the shin of the lower leg. The wearer immediately senses this pressure and can relate to the forces at work. A light strap 29 keeps the rod 23 vertical around the top of the lower leg. The overall assembly is comfortable and integrates into the wearer's sense of the applied forces.

Whereas in figure 2a the device must be tightly strapped to the leg, in figure 2b the exoskeleton can be worn like normal footwear, without any strapping at all, and can cater for a large range of user sizes and gait types since all the device does is introduce perpendicular forces roughly half way up the shin.

III. Prototype

In order to test the feasibility of the proposed approach a prototype was constructed which was named Hubot for Human assistive Robot.

There are three key features of Hubot; the exoskeleton, the air muscle and the power pack.

A. Exoskeleton

The first prototype of the exoskeleton was aimed at assisting the lower leg and specifically plantar flexion of the foot during either a rapid powerful motion, such as a jump, or during endurance walking.

The Hubot prototype is shown in Figure 3. It is made from aluminum square tubing and is integrated onto a normal running shoe. The device is simply worn as a running shoe.

The overall weight of the single foot device is 1.5Kg including the shoe, the exoskeleton and the air muscle assembly. The heavy duty aluminum square tubing used included a large margin of breaking strength and the next version of the prototype will be achieved with much lighter weight components.

Fig. 3. Front and side views of the Hubot lower leg wearable robotic device.

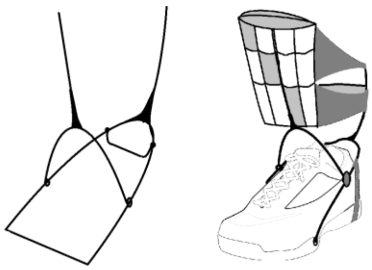

Fig. 4. Lighter weight Hubot frame LEFT showing the frame required RIGHT showing its integration with the shoe and air muscle.

Figure 4 shows how the assembly can be fabricated using reinforced carbon fiber rods, perhaps achieving a final weight of less than 800g including the shoe.

B. *Air Muscle*

The traditional McKibben air muscle used for example in [6] and [16] suffers from two disadvantages. The main disadvantage is the low contraction distance to total length ratio, which is usually around 25%. Since the air muscle in the proposed approach acts perpendicular to the human limb, the air muscle must be much shorter than if the muscle acted parallel to the long limb.Additionally the force McKibben air muscles produce tends to increase as a function of their length, since their circumference remains the same at the relaxed state.

In our paper [17] we presented a new type of air muscle as shown in figure 5. This air muscle has a contraction to length ratio of the order 100% to 200% and the force increases as a function of the area of the face. As a result much higher forces can be generated over a smaller distance and in a smaller volume. In figure 6 is shown the air muscle fabricated for this prototype under test. The device is made in a combination of latex internal sheath and denim outer layers with nylon stitching. It can lift a 16Kg load through 10 cm in 0.3 seconds at a supply pressure of 2 Bar. Typically, the contraction to relaxed length ratio is 120%.

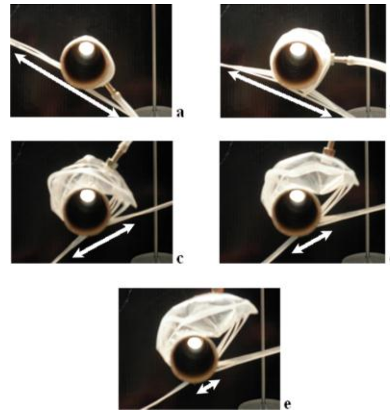

Fig. 5. This shows how the expansion of the air chamber converts to the contraction of the air muscle, see the arrow getting shorter, in the drive used in this work.

Fig. 6. Front and side views of the air muscle fabricated for this work, under test, the load of 16Kg is lifted 10cm in 0.3 seconds at 2 Bar.

C. *Back pack air compressor, battery and valves*

The Hubot prototype requires a source of compressed air to drive the air muscles. This is derived from a T-Max (Part No. 8016601) air compressor and a standard 12 volt gel 24Ah battery which is assembled into a backpack unit.

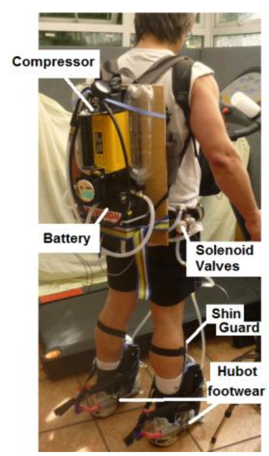

Fig. 7. Air compressor and battery back pack. Belt worn solenoid valves. Footwear worn with no straps and only as sports shoes.

The air solenoid valves controlling flow to the footwear are kept on a belt as they should ideally be as close as possible to the air muscles and will in future be moved to the footwear. Figure 7 shows the back pack and air solenoid valves of the fully tether less system.

IV. Testing and Results

A. Ease of fit and comfort

In order to determine the fit and comfort for the Hubot exoskeleton a simple set of metrics was devised.

The time to fit on the device is seen as an important aspect, since in future such devices might be used by emergency services and put on just before going into an emergency situation, where time is of the essence. The test was performed by simply asking 5 people to put on the suit as it currently exists in prototype form and recording the time in comparison to putting on similar attire (in this case a heavy knapsack and rubber water protective boots).

The comfort of the device is measured subjectively by asking people to wear it and rate the experience stating if the apparatus was very uncomfortable, acceptable for a short time, OK, comfortable, very comfortable.

As part of the energy trials to be performed in the next test, it was decided relevant to monitor the effect of wearing the apparatus on energy expenditure while the apparatus was in the switched off state so that we could determine if the suit was impeding normal efficient walking.

B. Athletic Performance Vertical Jump

One of the main attractions of wearable robotics is the possibility that one day we may be able to use them to augment our athletic capabilities during different situations. Within the sports science community a common metric for athleticism is the Vertical Jump Test. Devised in 1921 [18] the test requires that the athlete measure the height he can jump over and above the point he can touch with the tips of his fingers when that hand is fully raised while standing. A great deal of normative data has been gathered from world class athletes [19] supporting the method as a true test of athleticism. In [20] the data obtained from adult athletes suggests that for a male of 20+ years old a jump greater than 70cm above the standing line, is classed as excellent, while 50cm is average and below 31cm is poor. The test is aimed to assess explosive power and not endurance.

In the test to be conducted with the Hubot prototype device, the vertical jump test is to be executed exactly as sports science would require [21]. However for safety reasons it was decided that the tester would not wear the full backpack apparatus. Instead the wearer would only wear the active footwear and carry a compressed air tank ready filled from the compressor.

The tester would first perform the jump test in normal clothing. Then the jump would be repeated wearing only 1.5Kg weights on each foot. Then the jump would be performed with the Hubot prototype footwear. Finally, the jump would be performed with the Hubot prototype footwear and a 9 litre plastic (PET) air chamber prefilled to 3Bar.

Just before a jump is actually carried out, the person's knee is bent and the back of the thigh lies in full contact with the calf. For the final jump, to release air from the air chambers the separation of thigh and calf is used as the trigger to drive air into the air muscles. As soon as the feet lift off the ground the air pressure in the muscles and air chamber is released.

C. Athletic Performance Payload and Incline, Energy Expenditure

Benefits of Hubot towards endurance can be measured by estimating any potential savings in energy expenditure when using the device during walking.

During walking as the body's center of gravity passes over the foot the calf muscles begin to contract serving to control the body movement as it goes forward so that the body does not fall forward [25]. The calf muscle must suddenly support almost 3 times the body weight due to the moment arm between the Achilles tendon, the ankle and the joint between the metatarsus and tarsus. For the rest of the walking gait, efficient walking relies mainly on the leg swinging forwards and the body vaulting over the planted leg. Therefore the main energy component is in the calf muscle and dependent on the overall body weight.

The measurement of energy expenditure may be carried out using various types of devices and methods the most often quoted being maximal oxygen uptake during which the subject must wear a face mask connected to a gas analyzer. In [22] an extensive analysis is made which shows that heart rate can be used to make relatively accurate energy expenditure predictions. This was felt to be an adequate and convenient method for the sports like test that was required. In [22] the tests published the energy expenditure based on heart rate is provided and includes the subject's gender, heart rate, weight and age. For example applying the formula to a 54 year old man of 80Kg, the formula gives us the energy expenditure EE,

$$EE = -28 + 0.6309 \times \text{heart rate kJ/min}$$

The approach is only valid if the heart is beating above the FLEX heart rate, which differs for different people and states of fitness.

The steep incline test will use this approach to measure the energy expenditure as the test subject uses the Hubot prototype device to walk on an inclined treadmill.

The test is broken into four phases where each phase follows a similar pattern. This pattern is as follows. The test subject first relaxes for 10 minutes before the test. Then for two minutes the heart rate is recorded every 10 seconds as the subject stands on the treadmill. This is done in order to measure the FLEX heart rate (an average of the lowest heart rate recorded and the highest during this standing period). Then the treadmill, set at an incline of 5 degrees, is started at a speed of 3.3 Km per hour. The heart rate is then monitored for 5 minutes as the subject walks at a steady pace. This length of time was chosen since preliminary testing indicated that the heart rate did not change significantly after a 2 to 3 minute period. The treadmill used, V-fit T1-08 Treadmill SP1609-UK, includes a heart rate monitoring function and this was used and sampled manually every 10 seconds. The treadmill is set to a 10% incline throughout the tests.

In the first test phase, the test subject is wearing normal clothing.

In the second phase the test subject is wearing normal clothing, the Hubot backpack and a front pack weighing 17Kg to provide a higher payload for the test subject, in all totaling 33Kg. The test subject wears normal running shoes and a 1.5Kg ankle strap around each ankle. This test aims to obtain an energy expenditure measure that is not impaired by possible discomfort introduced by the footwear.

In the third phase the test subject wears the full Hubot apparatus and the front pack including the footwear, but the system is powered off. The aim is to check if wearing the footwear results in higher energy expenditure due to discomfort.

Fig. 8. Frame from the video capture of the fourth phase of steep incline endurance test.

In the fourth phase the test subject wears the full Hubot apparatus and the front pack. The Hubot prototype is now fully powered on at an operating pressure of 200 kPa. At each step on the treadmill, the user signals using a micro-switch attached to his thumb, when the valves should be activated. The release of air from the air muscle is automatic when the foot leaves the ground.

The main aim of test is to determine if the energy expenditure recorded while wearing the Hubot prototype device is lower when switched on compared to when it is switched off. Figure 8 shows the Hubot prototype in use and powered on during the fourth phase of the trial.

D. Results and Discussion

The results obtained provide useful information about the Hubot prototype ease of use, comfort and assistance in both explosive power and endurance modes.

Ease of fit and comfort: To establish fit and comfort the feedback from 5 students who were invited to wear the prototype was recorded.

The mean time to put on the footwear and back pack and solenoid belt was 55 seconds. Whereas to put on water resistant rubber boots and to strap on a single oxygen cylinder used in underwater diving averaged only 50 seconds. From this one can postulate that the ease of fit is acceptable in most emergency service or industry situations.

When asked about the general comfort the subjects all stressed that the weight of the footwear was excessive and at most should be equivalent to the rubber waterproof footwear which weighted 900g.

The subjects liked the fact that any running shoe could be modified to accept the Hubot frame since individuals had different shoe preferences.

The impact of the comfort of the footwear on the energy expenditure is treated in the following next section.

Athletic Performance Vertical Jump: The data presented here for the vertical jump test comes from only one test subject although more subjects are planned to take part.

Table I shows the condition of each jump, the average increase above the standing height for the jumps and a power rating calculated according to [23], which allows one to infer the peak power output of the test subject given the data and context. The results from jump 2 and 3 indicate that the wearing of ankle weights is roughly as hindering as wearing the inactive Hubot footwear since.

When the footwear is driven actively, Jump 4, the jump improves to a level above the plain clothes level, implying that the energy provided by the footwear overcomes the weight of the footwear as well as improves the test subject's explosive power.

TABLE I. VERTICAL JUMP RESULTS

Reference Height : 221cm	*Condition*	*Average Vertical Height above reference height for 3 best jumps*	*Power rating using Sayers Equation [22]*
Jump 1	Plain clothes	50cm	4740W
Jump 2	Plain clothes plus ankle weights	45cm	4436W
Jump 3	Hubot prototype inactive	44cm	4375W
Jump 4	Hubot prototype activated	55cm	5043W

Using Sayers formulae there is an increase in power of around 250W, which could be associated with the power provided by the air muscle. We know from tests that at the pressure setting each air muscle can deliver approximately 20Joules in 0.3 seconds (approximately 60W). The Hubot prototype comprises four air muscles fired simultaneously. Combined it is therefore estimated that the Hubot prototype could deliver 240W over the short period of the jump which would roughly agree with the results obtained.

Athletic Performance Payload and Incline, Energy Expenditure: This test was conducted with one test subject although more are planned.

The results obtained are based on the observed heart rate of the test subject. According to [24] when examining the heart rate to infer energy expenditure it is crucial that tests are carried out well above the FLEX heart rate such that inter individual differences become negligible and energy expenditure at different work rates may be accurately compared. Therefore for each phase of the tests the subject's heart rate was first measured before the physical exertion began in order to check the lowest and highest heart rate during relaxed and slight exercise (standing at an incline). From this the FLEX heart rate was calculated.

In all the tests presented the FLEX heart rate for the test subject was 81 BPM or less. When the test subject is recorded with a BPM above this figure we can be sure that the heart rates obtained not only reflect linearly the energy consumption of the subject, but also and crucially that we may compare the heart rates from different subsequent trials, inferring comparative energy expenditure. The results are summarized in Fig. 9. From the graphs, one can observe that all heart rates rise well above the FLEX heart rate after the first minute.

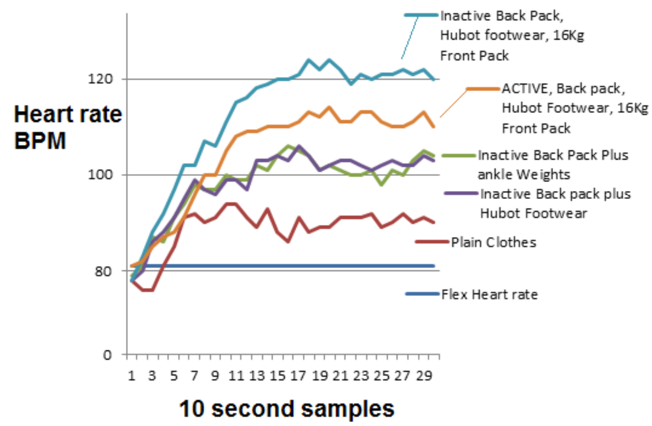

Fig. 9. Manually recorded heart rates for each phase of the testing.

For the plain clothes test the subject is walking up a mild incline with no additional weight. When the test is repeated wearing the 17Kg back pack, the energy expenditure inferred from the heart rate clearly rises. This test is done first with 1.5Kg ankle weights on each foot and then again with the Hubot footwear. In both tests the inferred energy expenditure appears to plateau at the same level.

This result adds to comments from test subjects and allows us to infer that the shape of the footwear does not impact energy expenditure and that the weight is far more critical. Therefore one conclusion is to keep the basic design but fabricate the footwear as light weight as possible.

When the test subject wears an additional 16Kg front pack, there is a marked increase in inferred energy expenditure. Since the relationships between the graphs may be considered linear, we can estimate that wearing the 16Kg front pack doubles the energy expenditure over wearing just the back pack, when compared to wearing just plain clothes.

When the Hubot prototype is powered up and the test repeated, while wearing the 16Kg front pack, the inferred energy expenditure falls to a point in between wearing both packs and wearing the back pack alone. The result indicates that the prototype has contributed to the total energy required to perform the walk and reduced the necessary energy spent by the test subject.

At this stage the intention is not to perform a detailed analysis of the power savings. The main purpose has been to demonstrate that the system functions and can reduce energy expenditure and therefore improve human endurance.

A logical next test, which was not possible to complete within time of writing, is to determine if the energy expenditure used to carry the back pack can be offset in full (or more) by the prototype. These results are encouraging and form solid material for future work.

V. Conclusion and future Work

A. Contribution to Exoskeleton based wearable robotics

In this research work, a prototype has been developed to demonstrate that an easy to wear, comfortable exoskeleton can be used to increase both powerful explosive actions as well as contribute to endurance tasks such as walking with high payload.

The results obtained strongly suggest that the proposed new approach to the use of contractive drives and exoskeletons are beneficial, practical and ergonomic.

The prototype produced explosive power enabling significantly improved vertical jump, however the improvement is small when compared to the weight of the back pack which was not worn during the tests. Therefore improved light weight air compression technology is crucial for this approach to be of use in the real world.

The air compressors available today are targeted at low cost, high pressure automobile tyre inflation where weight does not matter. With attention given to special materials and a low pressure mode of operation, the future availability of lighter compressors seems feasible

A key conclusion that the work has led to is that wearable robotics must be wearable and integral in the human actions being performed. Loose fitting devices whose drive forces act perpendicularly to limbs feel as if they are self-adhering to the limbs and no complex straps are required. They also feel as though they are truly assisting the user rather than controlling the user.

B. Future Work

The tests here were conducted with a 17Kg backpack comprising the main compressor and battery. Very recently we have reduced this to 8Kg and aim to finally achieve 6Kg. This will represent a less bulky solution. In future work the results will be expanded to test the device on more subjects. It is hoped that the tests will be conducted outdoors, using wearable ECG sensors to record overall energy expenditure of subjects and control subjects performing similar tasks, such as hill climbing carrying heavy loads.

Following this, the aim is to incorporate a torso and thigh assist section to the Hubot and determine its impact on sprinting and long distance running.

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