Soft Hand Exoskeleton for Adaptive Grasping Using a Compact Differential Mechanism

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Abstract The work proposes an underactuated design of a glove-like soft hand exoskeleton for grasping and lifting objects of varied shapes and sizes. Strings are used to flex all finger joints, assuming that finger anatomy of an impaired hand is intact. A pulley-based differential mechanism is designed to actuate all four fingers via a single motor to allow adaptive grasping. Two DC motors are used, one for flexion of all four fingers and the second for thumb flexion. Finger extension is passively achieved via elastic bands on the dorsal side. A prototype of the hand exoskeleton, weighing 300 g without battery is fabricated that occupies $100 \times 56\,\text{mm}^2$ space over the palmer side of the forearm. Novelty in the design lies in reducing the required length of the existing pulley-based differential mechanism from 20 cm to 10 cm. Lightweight, and compactness make the device portable. Performance of the soft exoskeleton is demonstrated via testing it on a healthy subject.

Keywords Soft hand exoskeleton · Finger flexion-extension · Differential mechanism size reduction · Artificial tendon pulley system

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1 Introduction

Post spinal cord/brain injuries or stroke, normal functioning of the hand may be partially/totally impaired. In such cases, anatomy of a human hand remains intact while only motor control is lost.

For such patients, this makes it comparatively easier to develop a lightweight compact device, which can enable them to perform diurnal tasks. Only an actuation mechanism needs to be designed.

Grasping and lifting common objects are some of the most basic tasks one needs in daily living. In literature, several designs for hand exoskeletons exist, aiming for actuation of all finger joints. This full acutation is essential for tasks wherein, independent joint control is important, such as fine motor tasks like, writing, painting etc. However, that makes the design complex, and requires intricate control system for even the tasks such as grasping and lifting, which a healthy person performs easily. Complexity exists because, the control system has to adjust with varying shapes and sizes of the objects user wants to grasp. Underactuation, i.e. not actuating all joints independently, helps overcome this problem. When less actuators are used, than the degrees of freedom present in the fingers, there is redundancy. Consequently, during flexion, fingers can adapt to the shape/size of the object to be grasped. Some designs exist in literature [1, 2] (related to implants and robotic hands) which demonstrate this capability, by use of differential mechanism in their actuation schemes. Differential mechanism allows the user to flex some fingers, even if others are held stationary. This helps in making successful contact with objects of different shapes and sizes, even though not all fingers make contact simultaneously. Grasp force can be increased thereafter.

Biomimetic exoskeleton designs are inspired by the human hand anatomy, with the aim to mimic the tendon pulley systems in the hand, which are responsible for finger flexion and extension (Fig. 1). Lee et al. [3] propose a biomimetic hand exosksleton, in which they use seven DC motors to actuate tendons and employ springs as a differential mechanism. However, springs limit the shape adaptability, and also, they may behave differently after few iterations if permanent extension occurs. In et al. [4, 5] and Kang et al. [6] introduce differential mechanisms which enable adaptive grasping of various objects having different shapes/sizes. Two DC motors are used, one for index and middle figures, and another for the thumb. They use a passive brake mechanism [7, 8] to prevent slacking in tendons and ensure the efficient working of mechanism. Kang et al. [6] use ‘U’ shape differential mechanism only for index and middle fingers. This mechanism cannot be employed for all four fingers as it generates large frictional force leading to a high motor load.

The present work employs a pulley-based differential mechanism and inextensible strings to design a soft hand exoskeleton for adaptive grasping. The exoskeleton is developed for lightweight, compactness, portability and less friction. All four fingers are flexed using a single actuator, through a differential mechanism. The notion is similar to the one described in [9] wherein the differential pulley mechanism is employed on the palm of a prosthetic hand. The design therein uses four pulleys

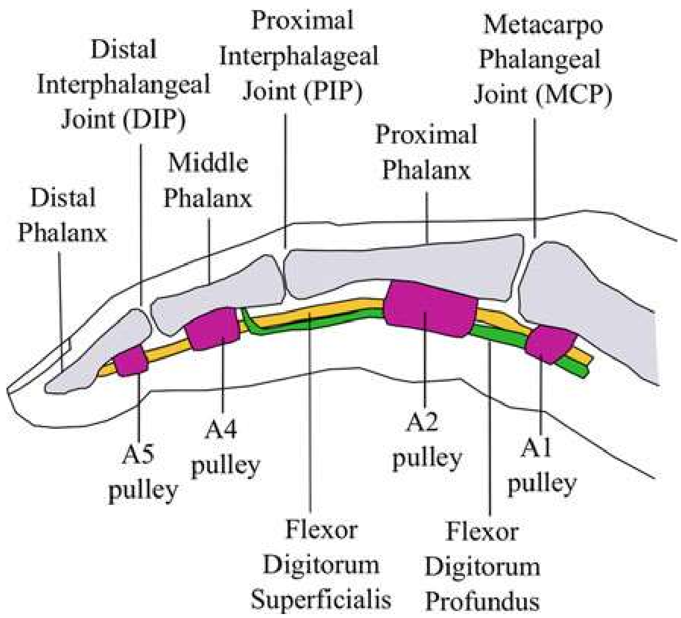

Fig. 1 Anatomy of a human finger: Tendon pulley system for finger flexion

whereas in the one proposed for an orthotic soft hand exoskeleton, seven moving pulleys and seven idlers are employed in multiple layers to reduce space over the forearm. The novelty is in the size reduction of the differential mechanism to obtain a compact design. In Sect. 2, design of a glove with tendon-pulley system, and a differential mechanism, CAD model, actuation and control are presented. The proposed design is tested and validated on a healthy subject (Sect. 3). Design aspects are discussed and lastly, conclusions are drawn in Sect. 4.

2 Exoskeleton Design

The presented design mimics the tendons responsible for finger flexion and extension via inextensible strings and elastic bands respectively. These strings are referred to as artificial tendons (Fig. 2a) in this paper. Pulleys responsible for maintaining these tendons close to hand are also replicated via inextensible string loops, referred to as artificial finger and palm pulleys. A woolen glove is used as an interface for the artificial tendon-pulley system. Tendons are actuated by a differential mechanism mounted on the forearm. Detailed explanation of the design is provided in the following subsections.

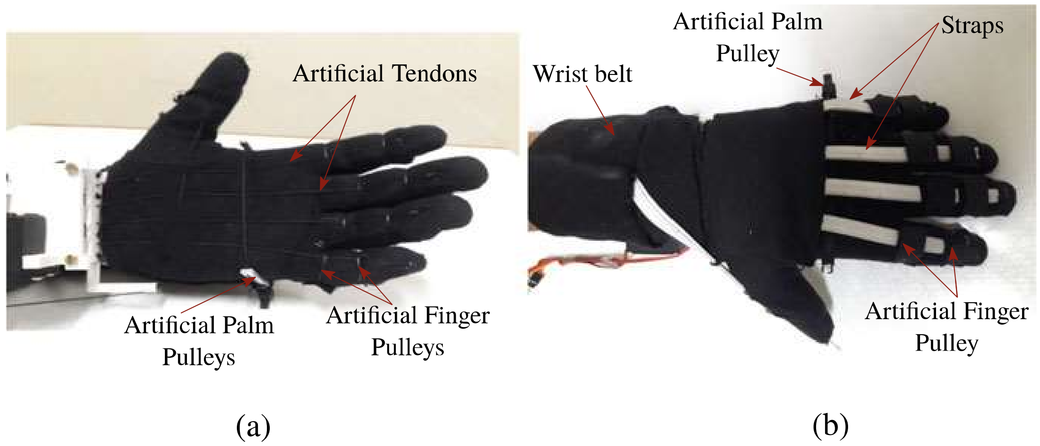

Fig. 2 Glove with **a** artificial tendon pulley system on palmer side for finger flexion, and **b** elastic straps on dorsal side for finger extension

2.1 Glove with Extensor and Flexor Tendon Pulley System

Artificial tendons and artificial finger pulleys are arranged like the flexor digitorum profundus (FDP) tendon pulley system found in biological fingers (Fig. 1). These tendons are attached to the distal phalanges, on their palmer side. Pulling these tendons flexes the three joints of a finger namely, the distal interphalangeal joint (DIP), proximal interphalageal joint (PIP) and metacarpophalangeal joint (MCP) (Figs. 1 and 2).

In case of the thumb, the artificial tendon actuates its MCP and IP joints.

Artificial tendons are woven in a flexible glove such as a woolen one. If these tendons are pulled as they are, they shift away from finger joints (phenomenon called bowstringing, Fig. 3). Consequently, the glove stretches and lifts away from the hand. This is undesirable as it interferes with the objects while gripping and may damage the glove. To avoid bowstringing, two sets of artificial pulleys are employed: (i) around finger, and (ii) on palm. Artificial finger pulleys are formed at middle and proximal phalanges of fingers, and proximal phalanx of thumb, using closed loops of inextensible string (Fig. 2). String loops are closed by securing Velcro straps attached at its ends (Fig. 4a). The straps make it easy to wear the glove, as well as, help in adjusting to different finger girths.

Implementation of a similar pulley (string loop) around palm, to prevent bowstringing near MCP joints, proves ineffective. This happens because, as these tendons are pulled, this pulley (string) also gets pulled away from hand, causing significant palm squeezing, as well as, bowstringing. To prevent this, a U shaped aluminum bracket is used around the palm, which eliminates contact between string and palm sides (Figs. 2 and 4b).

When artificial tendons are directly attached to the glove at distal phalanx, the glove stretches in proximal direction (Fig. 5a). Consequently, it interferes during grasping, and, damages the glove too. These problem is circumvented by using another pulley in form of string loop around distal phalanges, woven in the glove (Fig. 5b).

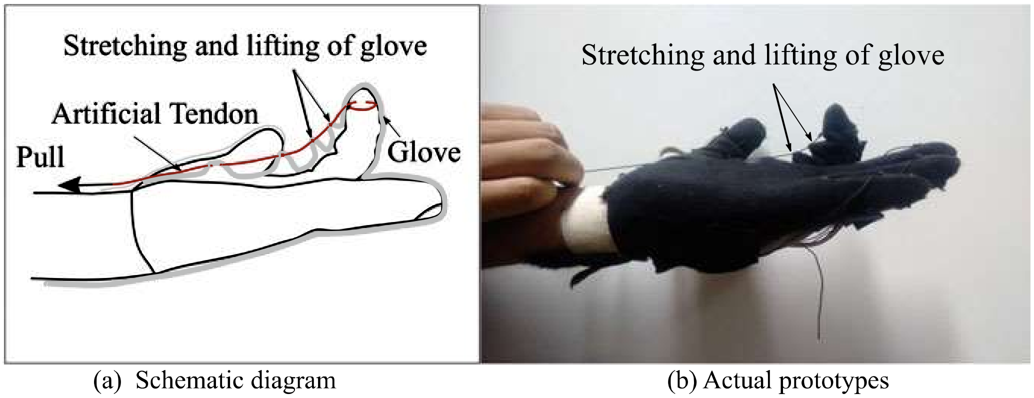

Fig. 3 **a** Schematic diagram and **b** Actual prototype showing lifting/stretching of the glove away from fingers and palm when AT is pulled (towards left)

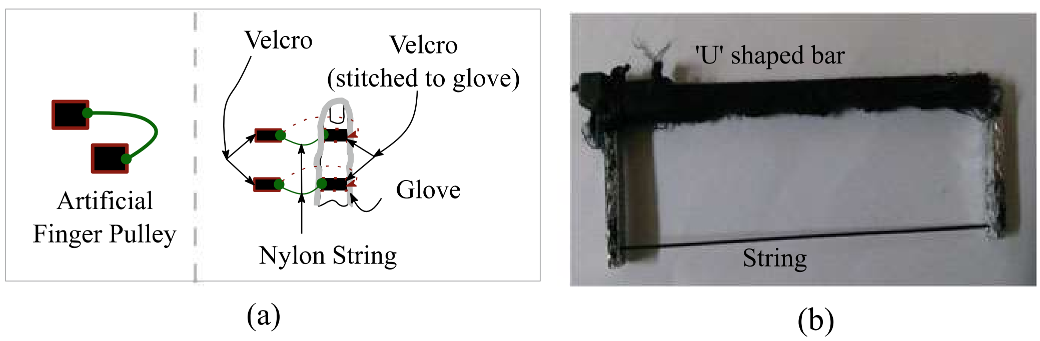

Fig. 4 Artificial Pulley design: **a** Pulleys around finger phalanges for preventing bowstring near PIP and DIP joints, **b** Pulley around palm for preventing bowstringing near MCP joint

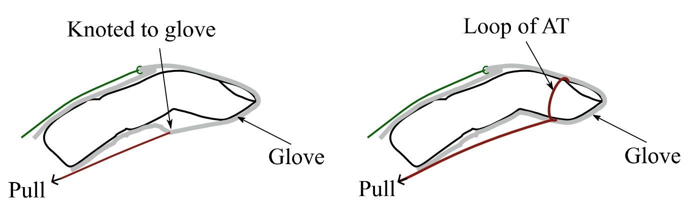

Fig. 5 Tendon attachment on distal phalanx: Attaching to a point on the glove leads to stretching. Solution is to wind a loop of the tendon (string) on the phalanx

Finger/thumb extension is performed passively by elastic bands. One band is attached to each of the five distal phalanges on their dorsal side. These bands are sewn onto the glove to terminate on the back of the hand (Fig. 2b). They are in relaxed state, in the fully extended configuration of the hand. Post flexion, when extension is desired, artificial flexor tendons are slackened, and, band elasticity helps the digits regain their fully extended states.

For finger flexion, the tendons are actuated via a differential mechanism discussed next. Thumb flexion is performed by directly actuating the corresponding tendon via a separate actuator.

2.2 Differential Mechanism

Similar to [9], the basic elementary unit of this mechanism is shown in Fig. 6a, wherein blocks and strings represent fingers and artificial tendons, respectively.

This unit has two degrees of freedom. Therefore, while moving the pulley, hindering the motion of one finger (block) does not prevent the motion of the other finger (block). At a given time instant, only the finger which offers lower resistance moves (Fig. 6b), when pulling force is just sufficient to cause uniform motion. In finger flexion, the tendon force (tendon tension) keeps increasing with flexion, in all fingers [10]. This means, as the finger with lower resistance flexes by some amount, its resistance increases, and can become higher than that of the other one. Then, the other finger starts flexing. This switch keeps happening, and both fingers get flexed consequently step by step. In practice, it is difficult to have identical resistance in both fingers. Therefore, simultaneous flexion does not happen. However, switching between fingers happens very fast, as only a very small differential in resistance is required to cause the switch. Thus, fingers appear to move simultaneously. In case fingers are being flexed to grasp an object, if a finger gets into contact with the object, it stops flexing further. Then, the other finger starts flexing faster, until this finger also makes contact. Thereafter, the grasping force starts increasing, if pulley is being exerted further force from the actuator. Based on these observations, this elementary unit can be employed to flex a pair of fingers for adaptive grasping via a single actuator.

To design the exoskeleton for actuating all four fingers for adaptive grasping, a pair of elementary units is connected via a third pulley (Fig. 7). This arrangement becomes a two-stage differential mechanism, such that, when the third pulley is pulled by an actuator, the pulley among P_1 and P_2 offering lower resistance moves at a time. Consequently, the finger offering least resistance moves at a time, as discussed earlier. All fingers keep flexing turn by turn, until some finger gets into contact with the object to be grasped. Rest of the fingers keep flexing, until each makes contact with the object. Then, the grasp force can be increased, by further increasing actuator input. In this way, fingers can grasp objects of varying shapes and sizes (adaptive grasping). Grasp force is also expected to be sufficient for diurnal activities, by use of an appropriately powerful actuator.

To flex a finger completely using the above design, strings directly attached to fingers, i.e. the blocks, should be pulled by around $d = 10\,\text{cm}$ for an adult human. Therefore, to close a fist, one needs a minimum $2d = 20\,\text{cm}$ space, as shown in Fig. 7. This excludes the pulley sizes. Yet, it is significantly large and will cover most of the forearm. Therefore, a strategy is adopted to reduce the longitudinal size of the differential mechanism in three stages.

In stage-1 (Fig. 8), two idler pulleys A_1, and A_2, are introduced to reverse the direction of motion of the pulley P_3. This reduces the required size to $3d/2 = 15\,\text{cm}$, excluding the pulley sizes. In stage-2 (Fig. 9), instead of connecting fingers directly to pulleys P_1 and P_2, intermediate pulleys P_4–P_7 are introduced. One end of the strings (artifical tendons) connecting to the fingers is fixed. This arrangement reduces the

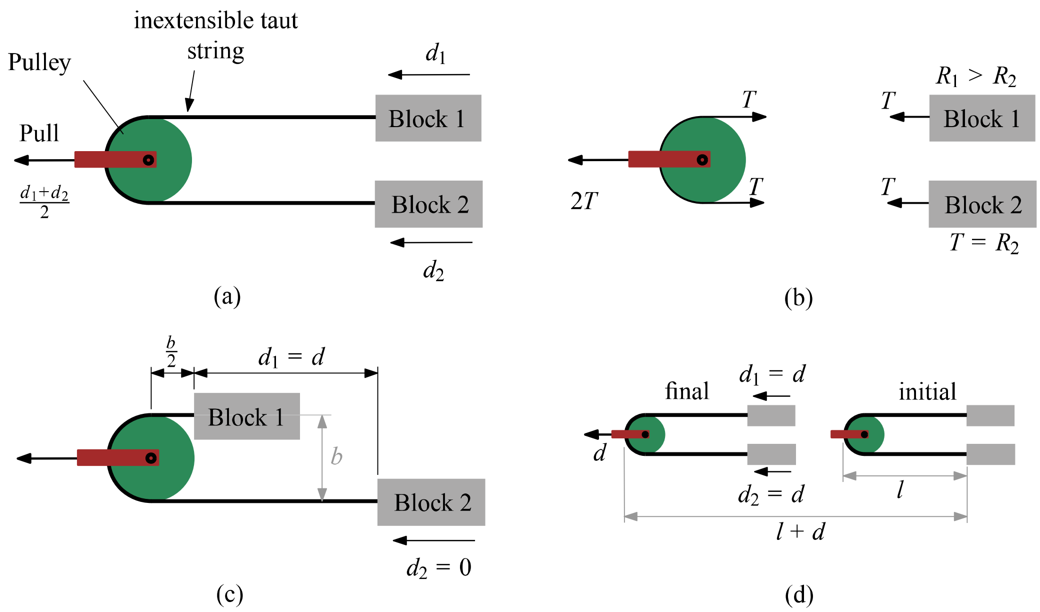

Fig. 6 Pulley-block system as a differential mechanism: **a** Kinematics: Two degrees of freedom: Out of the three elements (two blocks and one pulley), any two can move independently at a time, while maintaining the string taut. Pulley displacement has to be the average of block displacements d_1 and d_2. If one block stops moving, the other will move twice as fast as the pulley. **b** Statics: Starting from rest, if the blocks offer unequal resistances R_1, R_2 to motion, the string tension T increases until the less resistant block starts moving. Pulling force is therefore, twice the lower resistance value. Assumptions: (i) Pulley axis friction is negligible. (ii) Rolling friction (no slip) between string and pulley is negligible compared to string tension T. (iii) String is very light to be considered massless. (iv) Pulley inertia force (either mass or acceleration) small compared to string tension T. Under these assumptions, string tension T remains uniform over its entire length, and the pulling force is twice the tension T. **c** Design: Configuration with minimum distance between pulley and a block: If $d_1, d_2 \leq d$, the minimum string length required is $d + b + \pi b$. **d** Design: Configuration with maximum displacement: Length $l = d/2 + b$. Hence, minimum space needed for the assembly $= l + d = 3d/2 + b$

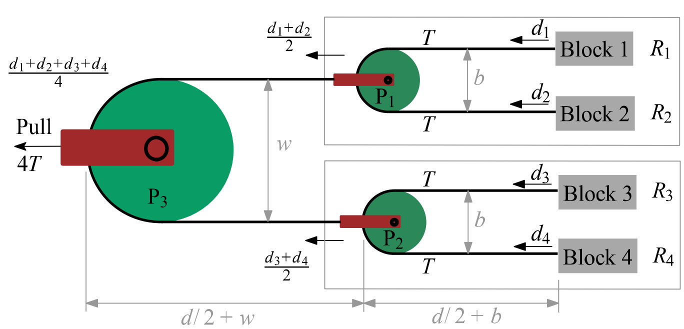

Fig. 7 Differential Mechanism for four fingers: Two pulley-block elements act as two separate blocks for the bigger pulley. Displacement of the bigger pulley is the average of all four block displacements. At a given time, only the block with lowest resistance will move, just like in Fig. 6, provided that pulley-3 is pulled with just enough force to cause motion. The pulling force will be four times the lowest resistance among the four. If $d_1, d_2, d_3, d_4 \leq d$, then, the maximum displacement of the smaller pulleys $= d$. Therefore, similar to Fig. 6d, the minimum longitudinal space needed for the entire assembly $= l + d = 2d + b + w$, where $l = d + b + w$. Lateral space required $= b + w$

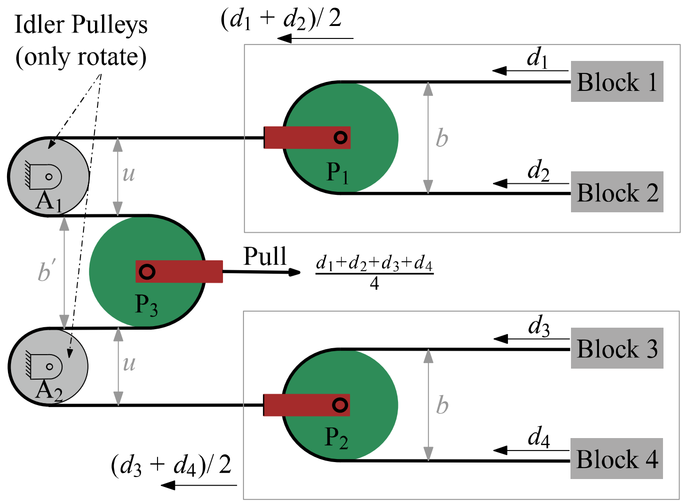

Fig. 8 Length reduction of the differential mechanism in Fig. 7: Stage-1 of the reduction: Two idler pulleys A_1, A_2 used to reverse the direction of the pulley P_3. Each of the two pulley-block subassemblies on the right, needs minimum space of $3d/2 + b$, as shown in Fig. 6, for block displacements $d_1, d_2, d_3, d_4 \leq d$. The pulley P_3 has the maximum displacement $= d$. Thus, the maximum longitudinal space need for the entire assembly $= 3d/2 + b + u$. Lateral space required $= b + b' + 2u$

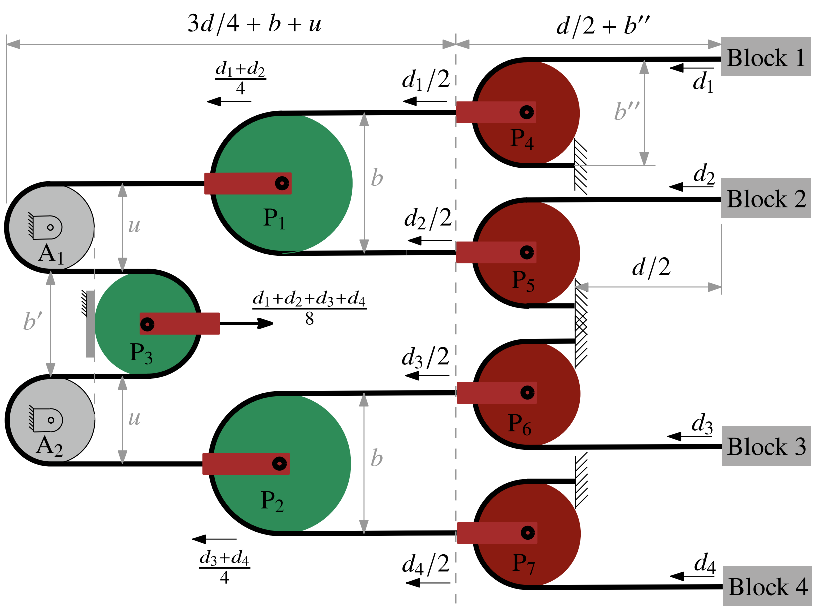

Fig. 9 Length reduction of the differential mechanism in Fig. 7: Stage-2 of the reduction: Each block in Fig. 8 is replaced by a pulley-block element with one end of the string fixed. These new pulleys P_4 - P_7 have maximum displacement $= d/2$ for block displacements $d_1, d_2, d_3, d_4 \leq d$. Other pulleys, therefore, have their maximum displacements halved to $d/2$. Comparing to Fig. 8, the logitudinal space requirement is reduced to $3d/4 + b + u$. However, addition of new pulleys increases it by $= d/2 + b''$. Hence, total longitudinal space needed $= 5d/4 + b + b'' + u$. Lateral space $= b + b' + b'' + 2u$

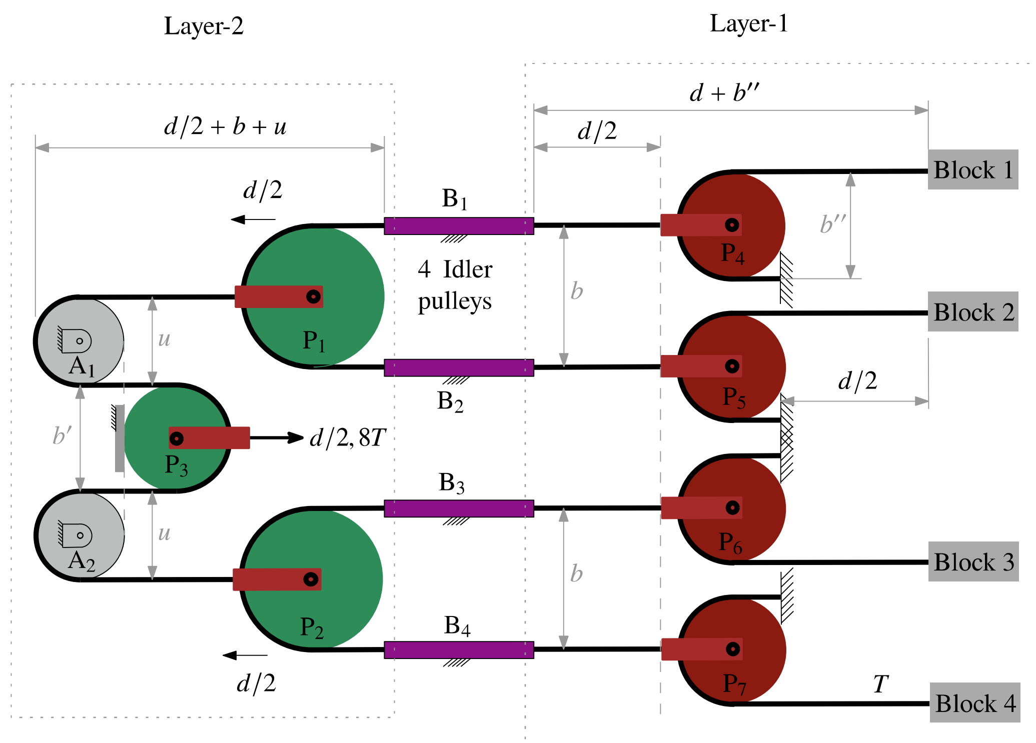

Fig. 10 Length reduction of the differential mechanism in Fig. 7: Stage-3 of the reduction: The design in Fig. 9 is split into two halves. Each half is stacked vertically in two layers. Four vertical idler pulleys B_1–B_4 are used to connect the two layers. This figure shows the two layers in single plane for visual clarity. All pulleys P_1–P_7 have maximum displacement $= d/2$ for block displacements $d_1, d_2, d_3, d_4 \leq d$. Logitudinal space requirement for the layer-1 is $d + b''$, which is more than that of the layer-2 ($= d/2 + b + u$). Hence, total longitudinal space needed by the entire assembly is $d + b'' + u'$, where u' is the diameter of idler pulleys B_1–B_4. Lateral space $= b + b' + b'' + 2u$. Note that, pulling force has doubled, as compared to the original design in Fig. 7. Longitudinal space is approximately halved ($d \gg b, b', b'', u, u', w$). Input pulley P_3 displacement is also halved

longitudinal size to $5d/4 = 12.5$ cm. However, it doubles the actuator force requirement, and halves actuator amplitude. To take advantage of this arrangement, four idler pulleys B_1–B_4 are introduced in stage-3 (Fig. 10). The design is split into two halves which are then, stacked over one another in two layers. This brings down the longitudinal size to $d = 10$ cm from the original 20 cm (ignoring pulley sizes). The compromizes required are, (i) increase in the lateral width and the height of the assembly, (ii) actuator force required is doubled, i.e. eight times the lowest resisting finger force, (iii) thirteen pulleys required, which might increase friction considerably compared to just three in the original design, if not properly designed.

To accommodate thumb motion, a hole is made in the frame of the differential mechanism, to pass the string (artificial tendon) coming from the thumb of the glove. The tendon is connected to motor directly. This allows the thumb to flex in the direction perpendicular to the axis of the hole.

Motors are mounted on the third layer of the assembly, and connected to the pulleys via strings passing over an idler pulley-C (Figs. 11 and 12). Figure 11 depicts

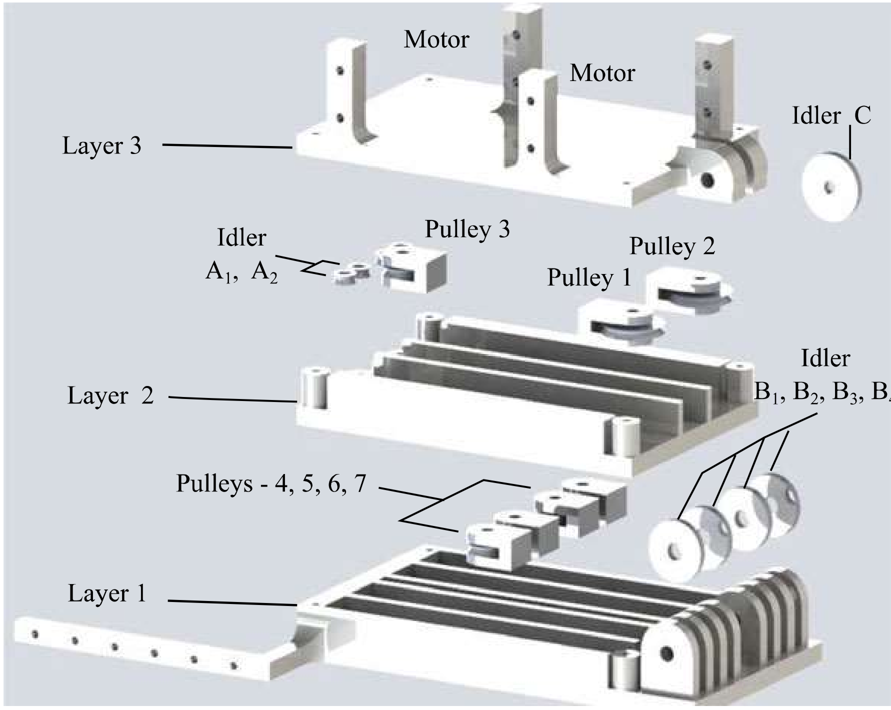

Fig. 11 CAD model: Exploded view, showing three layers. Layers 1, and 2 house the mechanism, while the actuators (motors) are assembled in the third (topmost) layer

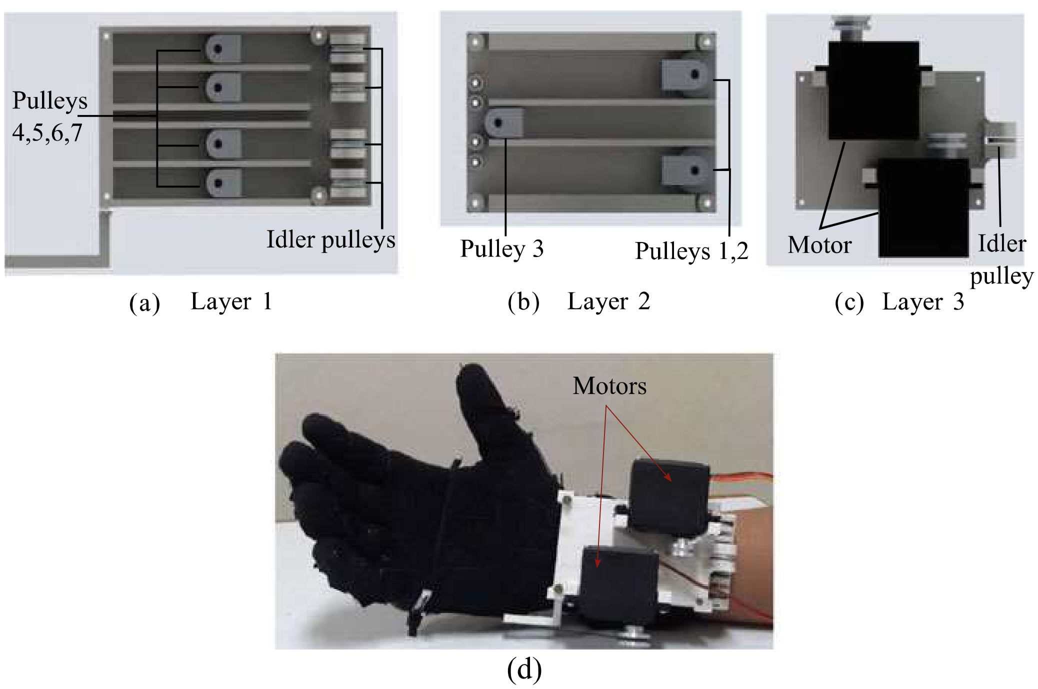

Fig. 12 Prototype of the soft hand exoskeleton: **a**, **b**, **c** show different layers (top view) in the differential mechanism. **d** shows the exosekleton in use

the CAD model of the final differential mechanism. A prototype of the final model, is fabricated which weighs 300 g and occupies $100 \times 56\,\mathrm{mm}^2$ on forearm (Fig. 12b).

2.3 Motor Selection and Control

Most daily tasks performed by hand require 10.5 N of force [11]. In et al. [4] proposed an empirical relation between the normal force applied by fingertip F_n and artificial tendon tension F_t using an experiment as:

$$F_\mathrm{n} = 0.38 F_\mathrm{t} \tag{1}$$

The maximum force exerted by the flexor digitorum profundus (FDP) muscle is approximately 140 N [12]. Therefore, the actuator which can pull the artificial tendons with 140 N (FDP muscle) is chosen. As per Eq. 1, we expect our soft hand exoskeleton to deliver maximum normal fingertip force of $0.38 \times 140 = 53$ N, which is well above the magnitude needed for daily tasks.

Motors are manually controlled by double pole double throw (DPDT) switches, which is expected to be operated by user's healthy hand (if feasible).

3 Tests and Validation

The exoskeleton is tested on a healthy 22 year old male subject. The subject is instructed to keep his hands free and loose, during all tests. The exoskeleton is mounted on his left hand, and is operated by the subject himself using his right hand (Fig. 13a). The subject is able to make fist (Fig. 13b), as well as, grasp and lift objects of different shapes and sizes (Fig. 13e–h). The adaptability is evident from the fact, that, blocking motion of some fingers, does not hinder other fingers (Fig. 13c, d). As control of ab/ad-duction is absent, thumb position is adjusted manually to hold the objects properly. In these tests, forearm, elbow and shoulder are controlled by the subject himself. Subject experiences uneasiness at distal phalanx, where tendon attachment loops apply squeezing pressure (Fig. 14). Similar uneasiness is experienced at the contact of wrist with the mechanism box, and at contact of palm bracket on dorsal side of hand, as circled in Fig. 14.

4 Discussion

The proposed soft hand exoskeleton uses two actuators to control fourteen degrees of freedom in hand responsible for finger/thumb flexion. The device weighs 300 g and occupies $100 \times 56\,\mathrm{mm}^2$ on forearm. It is lighter than most previous soft hand

(a) Healthy subject (b) Fist making (c) Obstructing 1 finger

(d) Obstructing 2 fingers (e) Grasping: Glass (f) Grasping: Cup

(g) Grasping: Brush (h) Grasping: Ball (i) Lifting Bag (>1kg)

Fig. 13 Various tests performed by a healthy subject: Subject is instructed to keep his digits loose, and, operate the DPDT switch by his other hand

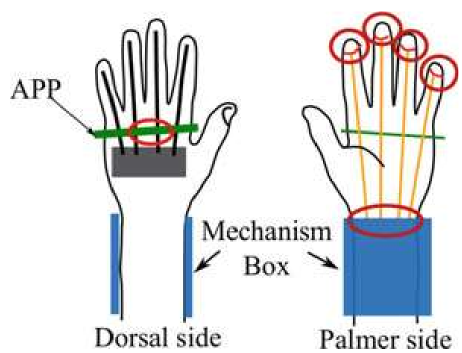

Fig. 14 Regions (circled) of uncomfortable contact forces

exoskeletons, e.g., 1 kg [3], 194 g (only glove part) [5]. Lightweight and compactness of the exoskeleton makes it easily portable, comfortable to wear and use. The device has low friction, as evident from the fact that all four fingers are actuated by a single motor. It was not possible in the design presented by Kang [5, 6] wherein ‘U’ shaped tubes were used which increased friction abruptly. In addition, one can further reduce the frictional force in this design by using pulleys with bearings.

The size of the existing pulley based differential mechanism, has been reduced considerably from 20 cm of length to 10 cm. Without the reduction, the corresponding mechanism would occupy most of the forearm area. The proposed reduction makes the device compact, and portable. The motor rotation required for the same flexion is reduced, whereas, motor torque requirement gets doubled. Number of pulleys has significantly increased from three to fourteen, which might increase friction significantly, if lubrication/bearings are not used in pulleys.

There are some limitations of this design. User can operate the exoskeleton using his/her healthy hand, if feasible. This is difficult, if both hands are disfunctional. As mechanism is underactuated, different independent control of fingers/joints is not possible. As a consequence, many activities cannot be performed, such as, squeezing of a spherical sponge ball, which requires flexion of DIP and MIP joint independent of PIP joint. Effective gripping of bigger spherical ball, which demands ab/ad-duction of fingers is also not possible. Grasping of objects, via fingers, of varied shapes and sizes is well achieved by using a single motor actuated mechanism. Implemented mechanism for flexion of thumb does not cover the complete range of motion required for gripping all type of objects. Similar to flexion, ab/ad-duction of thumb could be controlled via a pair of an elastic strap and an artificial tendon, connecting digit of thumb to an additional actuator. This would enable exoskeleton to grip a wide range of objects.

Assistance would be needed by an impaired subject to wear the glove. As the glove is close and opaque, it would be difficult for the subject to insert his/her impaired fingers into corresponding fingers of glove on his own. Semi-closed glove could be designed, enhancing visibility and reachablity of fingers, thus easing wearability.

When intentionally/accidentally finger(s) or/and wrist is/are flexed by subject himself or gets flexed by any external means, other than motor, the artificial tendons slack and become prone to slip off any mechanical pulley employed in mechanism. Provision of cover over pulley might resolve this issue.

The tendon lengths are subjected to user's hand. Instead of knotting the tendons to glove at distal phalanx, a better way should be explored, to tune the tendon lengths as per the user's finger length. User experiences uncomfortable contact forces at multiple locations (Fig. 14). Cushioning at these regions would enhance the user experience.

The presented soft hand exoskeleton is an attempt in the direction to provide a user friendly solution to people with impaired hand(s). The device must be tested on many patients to validate the feasiblity and to explore the unencountered challenges associated with it. Some possible modifications in this regard could be (i) if both hand are impaired, device could be controlled by some other means e.g. voice or leg, (ii) for people with wrist or/and elbow or/and shoulder impairment, the device could be coupled with other assisting devices. Use of elastic straps for extension of fingers and thumb is not a reliable solution in long run. Some alternative extensors may be explored.

5 Conclusion

Size reduction of the pulley-based differential mechanism allows us to develop a compact lightweight soft hand exoskeleton. The entire assembly occupies much smaller space (10 cm of length on forearm) than, without the reduction which would cover most of the forearm (atleast 20 cm of length). While the design provides a proof of concept for a wearable hand exoskeleton that exhibits adaptive grasping, further research is required before the proposed design becomes useful and amenable to the beneficiaries.

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