A NOVEL CONSTRUCTION AND MECHANICAL PRINCIPLES OF FIVE-FINGERED PROSTHETIC HAND

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This paper presents idea flow, development and construction of an anthropomorphic hand which is intended to be used mainly in prosthetics. Fundamental results of simulations and optimization of grasp are shown. The prototype has been manufactured and the principal functionality of finger mechanism (drive three axes by one string) has been tested. A new mechanical principle has been developed which is based again on an idea of using less actuators then joints with keeping adaptability and functionality of the mechanism.

Keywords: *prosthetic, grasp, EMG, hand, biomechanics*

1. Introduction

The current state in a field of commercial prosthetic hands is such that probably only one producer has a device with an opposition of the thumb [1]. All others are just any kinds of pliers such [2], [3] or [4].

If we have a look on mechanical constructions in research of the prostheses all of them has opposition of thumb but they are either reduced on number of degrees of freedom [5], [6], [7] or reduced on force performance by preloaded backward elastic elements [8], [9], [10] or has unideal adaptability of a grasp [11], [6] or both disadvantages mentioned above [12], [13]. Alternatively they are using 'alternatives' of actuation like hydraulic systems [14], [15], pneumatic systems [16] or shape memory alloys [17] which bring quite a lot of complications and complexity. Some of construction has insignificant number reduction of degrees of freedom they has good force parameters and kinematic behavior but they are very complex = expensive [18], [19], [20].

Construction described in this paper with contingent usage of new innovation of mechanical principle (described in paper too) is able to reduce all this disadvantages mentioned above – enough degrees of freedom (very adaptive grasps), sufficient force capability, simple (cheap, light weight) construction.

Very good mechanical construction is possible to find in robotics hands like [21] or [22] but they are not usable in prosthetic because of high weight and actuators are not implemented in palm (unappropriate dimensions). However prosthetic hand described in this article would be possible use as a robotic hand [23].

2. Methods and ideas flow

This chapter shows all ideas, methods and tools comes from inspiration by the nature [24], [25].

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2.1. Assembly of levers

The layout of muscles and related tendons on physical forearm is on Figure 1. If we consider Muscle Flexor Digitorum Profundus as a one actuator (in our case DC motor) we need another device such as a divider of force to divide power toward individual fingers. The nature solve this problem by partial innervation of muscle toward a particular tendon. So by one muscle is possible to control more tendons. Therefore assembly of levers were designed to divide the force from one DC motor to the five fingers Figure 2.

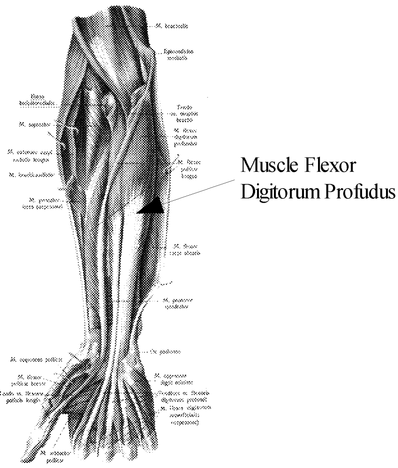

Fig.1: Muscles of the forearm – right side, front view; third layer (illustrative figure only, source [24])

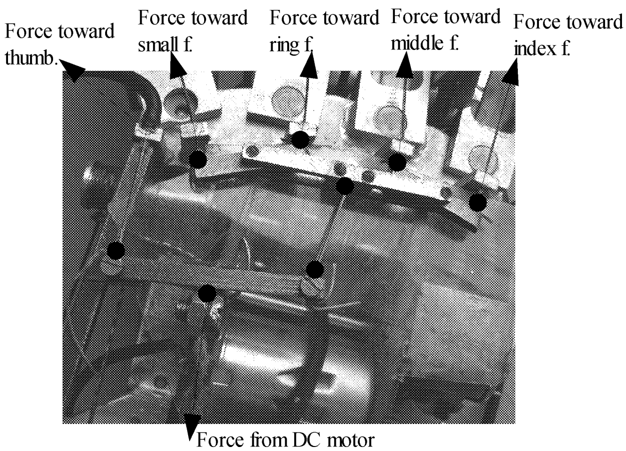

Fig.2: Assembly of Levers

2.2. Principle used inside of the each finger and realization of a duction

If we continue in an investigation of human hand toward tips of fingers we can find that each joint is actuated by own tendon (Figure 3) leaded from different layer of muscles and more over some joints are supported by other muscles (Figure 4).

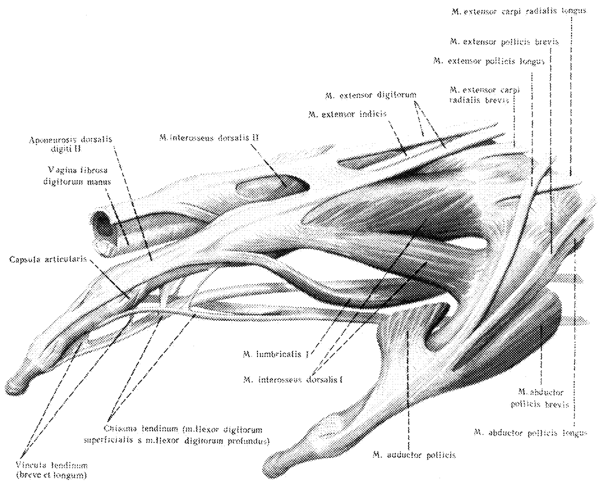

Fig.3: Layout of muscles and tendons in a finger (illustrative figure only, source [24])

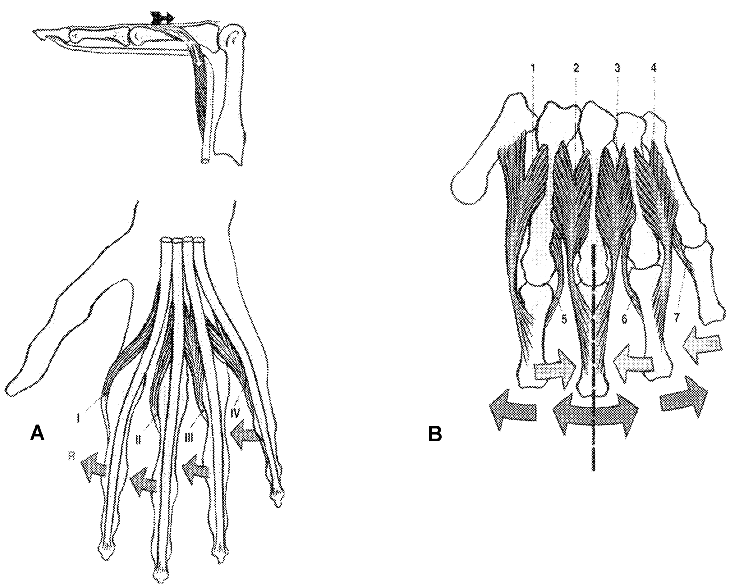

Fig.4: Schematic of muscle functions and layout (m. lumbricales (A) and m. inlerossei (B); a musculi lumbricales; right hand; view from front top – schematic of coverage m. lumbricalis against metakarpofalange joint and against interfalange joints by tension behind dorsal aponcurose of finger; side view I-IV m. lumbricalis I-IV; B musculi interossei; left hand; dorsum side view 1–4 mm interossei dorsales 5–7 mm interossei palmares) (illustrative figure only, source [24])

It means that we should use for each joint (DIP – distal interphalangeal, PIP – proximal interphalangeal) one and for some joints (MCP – metacarpophalangeal) more actuators. Question is if human hand is able to bend each finger in each joint separately and if it is needed in every day life. On the base of this consideration we can build up simplified mechanism showed on Figure 5. Which have been used at first prototype (Figure 6).

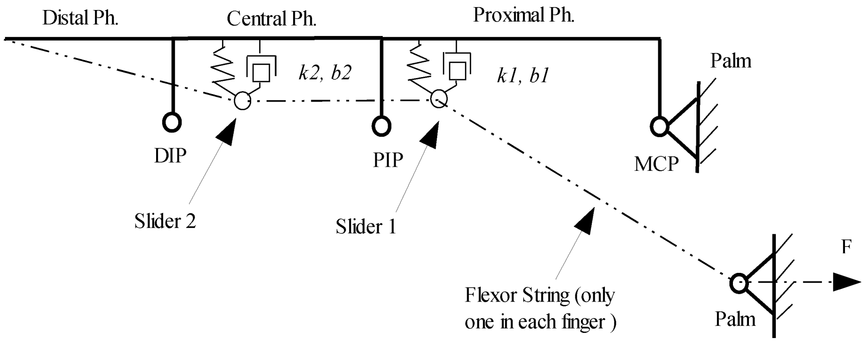

Fig.5: Principle of finger mechanism

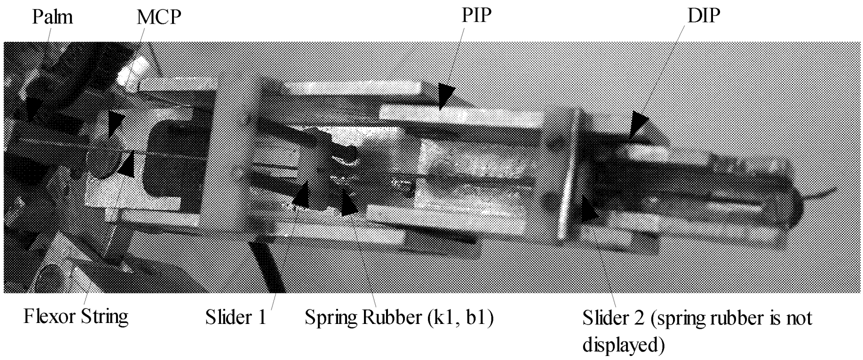

Fig.6: Principle of finger mechanism – prototype

Mechanism works this way: A force F is applied by a string which leads through two sliders (Slider 1, Slider 2). Connection between slider and phalange is realized by springs (k1, k2, b1, b2 – power rubber). Therefore the first motion generated when the string is pulled is in the MCP joint. Other joints can be activated only if the slider is under the appropriate joint. The PIP moves only if Slider 2 is under its (PIP) joint and the DIP joint moves only if Slider 1 is going under DIP joint.

Duction of fingers is realized by leading a string 1.5 mm beside MCP vertical axle. See Figure 7. System of strings leading around the MCP axes is designed to keep operation of prosthesis thus that when hand closes the adduction of four fingers is performed and when

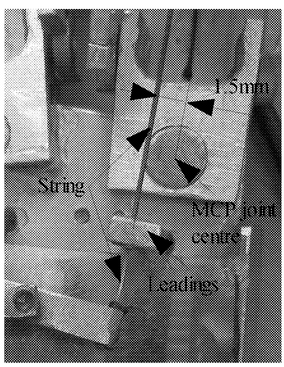

Fig.7: Realization of duction

the prosthesis opens the fingers do the abduction. Middle finger is without duction and it is intent to be used for precious pinch grasp.

3. Results

3.1. 3D model and computer simulations – grasp optimization

The 3D model on the base of ideas mentioned above have been created. With this model some basic analysis (kinematic, dynamical, structural) were done under very simplified marginal conditions. To describe all result is over this article. See [26]. Just for illustration behavior of the mechanism shows Figure 8. There is resultant of velocity on the tips of the fingers in global coordinate system located in the wrist (Figure 9) during movement from fully opened hand to fully closed. The step 140N force have been applied to each finger. Very fast changes in velocity (position, acceleration too) are brought up which are caused by mechanism principle used and very ideal conditions of simulation (no friction, gravity, dumping, effects of rubber glove, environment, ...) so this results give just rough but useful information of mechanism behavior.

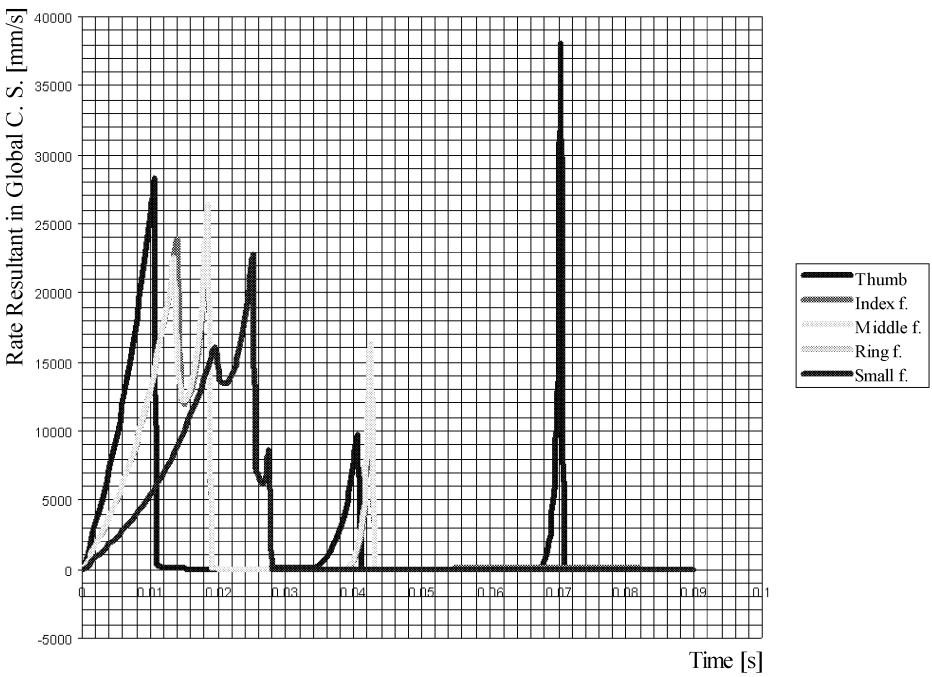

Fig.8: Velocity resultants for each tip point of fingers (illustrative figure only, values are not representing real state, for details see previous page)

The kinematic simulation showed that proposed angle of opposition of thumb against four fingers and applied forces to each finger were not appropriate to keep ball (100 mm diameter) stable in the hand. Therefore optimization (system Pro/Mechanica – Motion) was used to obtain force value for each finger and sufficient start angle of opposition of thumb for this type of grasp – grasp of 100 mm diameter ball which is considered as a basic one.

As a goal of optimization was to find a minimal or zero value of resultant virtual joint between ball and palm located in Point 1 Figure 9 in plain XZ and angle of opposition

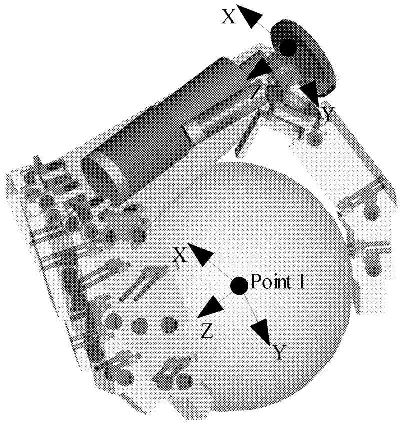

Fig.9: Model composition for optimization

of thumb see Figure 10. What correspond with consideration to keep ball stable in given layout of fingers. Before optimization ball was escaping from the grasp on more opened side – between thumb and small finger.

Parameters of last attempt to optimize this grasp with goal described above are in Table 1.

Parameter	Min. value	Initial value	Max. value	units
Thumb force	−350	−290.1	−230	N
Index f. force	−150	−100.9	−50	N
Middle f. force	−150	−100.2	−50	N
Ring f. force	−150	−99.51	−50	N
Small f. force	−150	−98.95	−50	N
Thumb angle	1.5	1.932	2.5	rad

Tab.1: Initial and allowed ranges of parameters

Optimization Convergence Tolerance: 0.1 %.

Maximum Number of Optimization Iterations: 30.

The initial values of parameters were find during some ancestral optimizations attempts.

After three iterations and 53 calls goal/limit function these results are given in Table 2.

Parameter	Optimized value	Ratio
Thumb force	−290 N	42.2 %
Index f. force	−100 N	14.6%
Middle f. force	−99.7 N	14.5 %
Ring f. force	−99 N	14.4 %
Small f. force	−98.5 N	14.3 %
Thumb angle	1.9 rad	—
Goal of opt.	0.183 N	—
Sum of applied force	687.2 N	100 %

Tab.2: Results of final optimization

The value of goal was accepted as a satisfactory value what has been validate by successful consequential motion simulation. Dimensions of levers (Figure 2) – force layout – were determined on the base of this optimization.

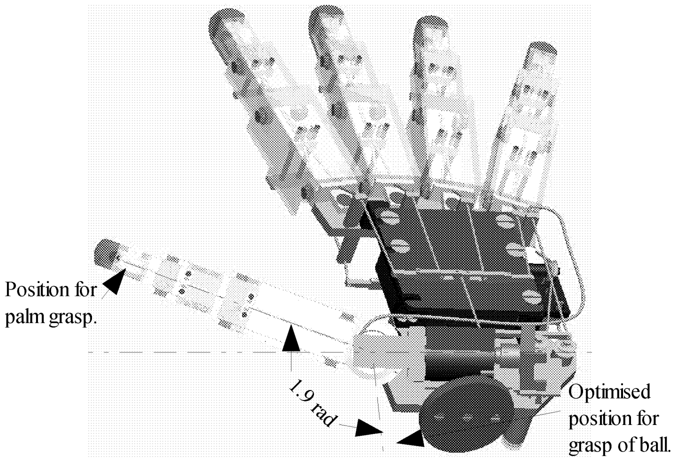

Fig.10: Measurement of angle of thumb opposition

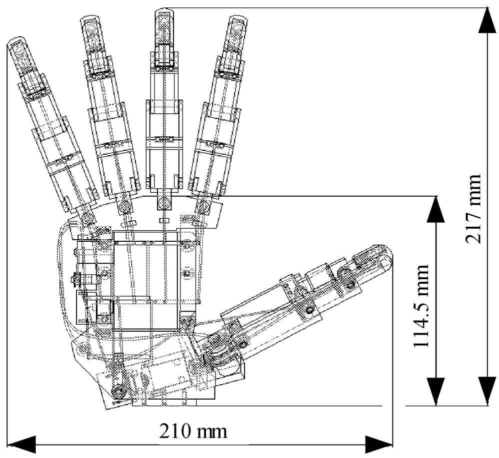

Fig.11: Global dimensions of 3D model

For complete information about 3D model the all fingers are dimensionally same and Figure 11 shows overall dimensions.

3.2. Prototype

First prototype (Figure 12) was designed to verify kinematical principle described above and for implementation of preliminary control system [27].

Final design parameters of this device are: Degrees of freedom: 21; Number of DC motors: 3; Kind of DC motors: Como Drills – 3Vdc, RE280, gearbox ratio: 1:256, escap MA16 16M 18 208 486 0, escap MA16 16C 11 207 365 0

Used materials: Main parts are from alloy of aluminum; bearings and sliders are from plastics; joint pins and assembly of lever from steel. As a strings have been used fish wire which has been found as appropriate solution with regard to dimensionality and strength.

Dimensions: Approximately rough external dimensions of open hand from dorsal (or palmar) view are 210×217 mm.

Reached parameters: Time to close (close and open) : 6 s (12 s); Force on the tip of index finger: see Discussion; Force of rude palmar grasp : see Discussion; Weight : 960 g; Cost : somewhere around 150 Eur (see Discussion).

There is probably only one part at Figure 12 what need little explanation and it is 'Tensioner'. This is used for compensation of non equality of consumption of string during closing and opening. For closing less length of string is needed (palmar side) then for opening (dorsal side). This difference is around 2 cm. Using of this complication bringing device should resolve innovation.

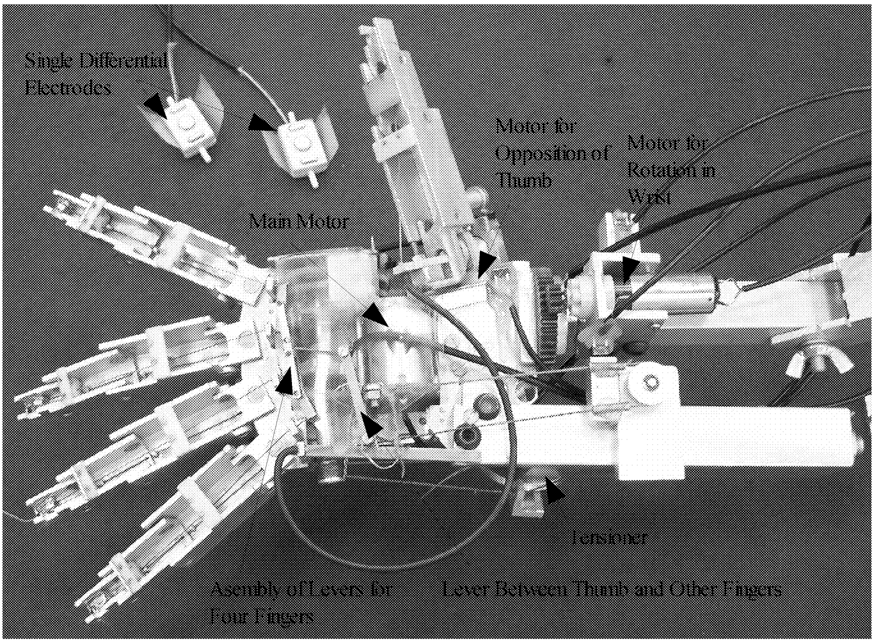

Fig.12: Prototype

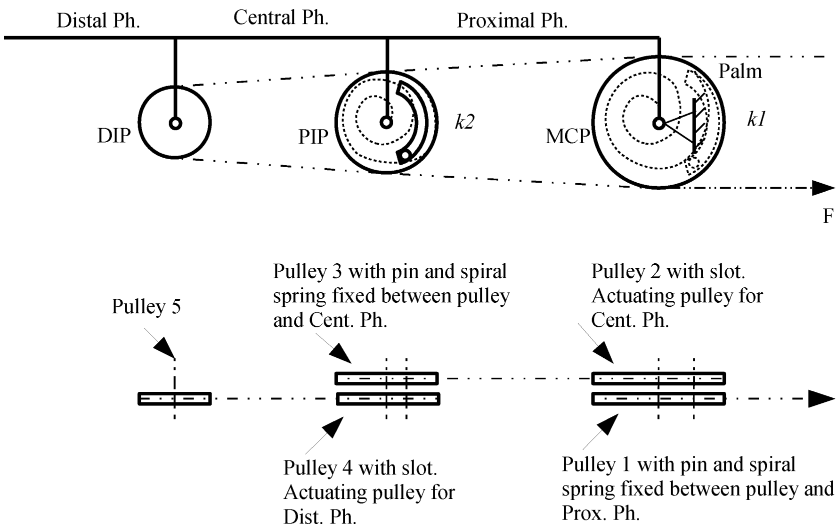

Fig.13: New generation of mechanical principle for fingers

3.3. Final innovation

All this results flow into major innovation of the mechanical principle (Figure 13).

Main difference from first principle is that rotary motion (pulleys) is used instead translation motion (string, sliders). Operation of this principle is as follow. Main force F is applied on Pulley 1 (P1) which share shaft with Pulley 2 (P2). Shaft is rigidly connected with phalange. Connection between P1 and shaft is realised by spiral spring (clock spring) and between P2 and shaft is free rotary connection. P1 is equipped with pin which moves in slot in P2. This slot is appropriate angle what is needed for full movement range of proximal phalange so when pin reaches end of slot P2 is going to move. Proximal phalange is on the end of its movement and movement of central ph. is started. This principle is spread over other joint. Pulley 5 is rigidly connected with distal ph.

Assembly of levers is replaced by system of pulleys (Figure 14).

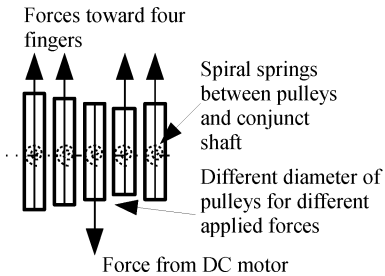

Fig.14: System of pulleys

System consists of 5 pulleys which are on one shaft and connection between each pulley and shaft is again realised by spiral spring. If we want absolutely same behaviour of this system as behavior of assembly of levers all pulleys should have spiral spring however probably pulley connected toward main DC motor can be connected rigidly to shaft.

To get appropriate kinematic behaviour (similar to human hand) it is ôonlyö dependent on how will be designed dimensions of all pulleys and length and stiffness of spiral springs.

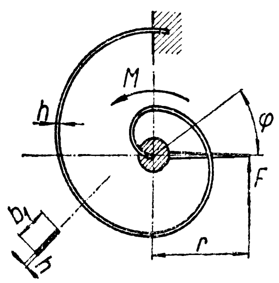

Fig.15: Spiral spring

Equations related are ([28] and [29]):

Relation between angle latitude and stress in a spring can be expressed:

$$\varphi = \frac{F}{E\,J}\,l\,r = 12\,\frac{F\,l\,r}{E\,b\,h^3} = 2\,\frac{l}{h}\,\frac{\sigma_0}{E}\ \text{[rad]}\ . \tag{1}$$

Relation between applied force and stress in a spring:

$$F = \frac{b\,h^2}{6}\,\frac{\sigma_0}{r}\ [\mathrm{N}]\ . \tag{2}$$

Equation 1 and 2 will be used just for tune of stiffness and angle latitude to insure kinematic properties of device:

$$k = \frac{M}{\varphi} = \frac{F\,r}{\varphi} = \frac{b\,h^3}{12\,l}\,E\ [\mathrm{Nm\,rad^{-1}}]\ . \tag{3}$$

The springs are not force springs but only kinematic one.

4. Discussion

Most of the computer simulations on the 3D model were not usable because predictions were very ideal (no friction, no gravity, no resistance of cosmetic rubber glove) but we obtained raw picture of behavior of the mechanism. Optimization of the grasp of a 100 mm ball brought quite useful percentage layout of the forces for balanced grasp which can be probably used for innovated mechanism too.

Prototype described above was finally verification model only of proposed kinematic mechanism on which could be applied control algorithm [27]. From these reasons the proper motors are not used and it is insignificant to measure force or time to close or open the hand. The weight is not comparable with any competitive device because the materials are again just low cost materials therefore the price is not factual too.

All this mentioned premises should fix next (re)design. To get appropriate kinematic behavior (similar to human hand) is ‘only’ dependent on how will be designed dimensions of all pulleys, length and stiffness of spiral springs. Which maybe will need new optimization which can be closely connect with optimization contact forces of the prosthesis [30]. The thumb will get its own motor and after that a precious pinch grasp will be possible to realize. The tensioner will be substituted by assembly of pulleys Figure 14. New mechanical design will take to the account possibilities of using device in robotic and industrial field as well as integration toward body [31], [32] and sensing system [33]. To easily redesign prosthesis from child hood size to adult hand size the parametric model based on kind of biometric dimensions will be used [34], [35].

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