

Bowden Cable Based Powered Ball and Socket Wrist Actuator

Samee Ahmad, Adnan Masood, Umar S. Khan

Abstract—A 2-Degrees of freedom powered prosthetic wrist actuator has been proposed that can provide the Abduction/Adduction & Flexion/Extension movements of the human wrist. The basic structure of the actuator is a Ball and Socket joint and the force is transmitted from the DC geared servo motors to the joint through the Bowden cables. The proposed design is capable of providing the required DOF in both axes i.e. 85° & 90° in flexion extension axis. The size and weight of the actuator lies within the ranges of an average human being's wrist.

Keywords—Actuator, Ball & Socket, Bowden Cable, Prosthetic, Wrist

I. INTRODUCTION

THE usual motions associated with the human wrist are the Flexion/Extension, Abduction/Adduction and the Pronosupination motions. The first two motions are the motions that are caused by the wrist joint itself and the third motion is actually the motion of the forearm. So the design of the prosthetic wrist joint has to essentially include the first two motions. The ranges of the motion of the wrist joint are:

Abduction : 15°
Adduction : 45°
Flexion : 85°
Extension : 90°

The main requirements for the design of a prosthetic wrist actuator are that it should be capable of providing the required degrees of freedom, it should be light in weight, should provide the required amount of torque/force and its size should be equal to or less than the size of the human joint that it will be replacing.

Little research has been done on the development of powered prosthetic wrist joints that can provide the Abduction/Adduction and the Flexion/Extension axis. One of them is a wrist designed for the DARPA RP 2009 robotic prosthetic arm [1]. Not a lot of information is available on the design characteristics of this prosthetic arm. Another is the ARTS Wrist that is created by an Italian engineer [2].

This wrist design uses the flexible Bowden cables for the force transmission and the end plate with which the hand is attached is connected with the help of a spring. The spring acts as a compliant surrogate of a universal joint [2].

The “Two-degree-of-freedom Powered Prosthetic Wrist” [3] provides the Pronosupination motion and the flexion/extension movements of the wrist joint. This research utilizes a mechanical differential mechanism to attain the movements which makes the wrist actuator heavy.

The research conducted in [4] is on the forward kinematics and work space analysis of a 7-DOF humanoid arm that proposes using a ball & socket joint in its wrist with the force transmission provided by Bowden cables. This research only provides the kinematics and workspace analysis and does not give any mechanical design.

In this paper the actuator that is proposed has two degrees of freedom that are Abduction/Adduction and Flexion/Extension movements. The Actuator is actually a modified Ball & Socket joint. The force transmission to the joint from the DC geared motor is with the help of Bowden cables. The weight and size of the actuator are selected considering the average values of the human wrist. The torque values are also selected from the study of the values required by the human user in the normal tasks of picking and placing.

II. MECHANICAL STRUCTURE

The basic structure of the proposed wrist actuator is a modified Ball & Socket joint. A frame is attached to the shaft connecting the wrist and the elbow joint which carries the DC geared motors. Most commercially available Ball & Socket joints provide 15° - 25° rotations [5], [6], [7] but the design requirement of the proposed system is that the flexion/Extension axis should be able to provide 85° and 90° of rotation respectively. For this purpose a modification has been done in the socket of the Ball & Socket joint. The socket of the conventional joints cover almost 75-80% of the surface area of the ball where as the modification is done so that the socket of the proposed Ball & Socket joint covers only 25-30% of the surface area of the ball. This low surface contact allows the socket to rotate more than the conventional sockets. Another modification is that the socket has four eye-rings with which the flexible Bowden cables are attached for the force transmission.

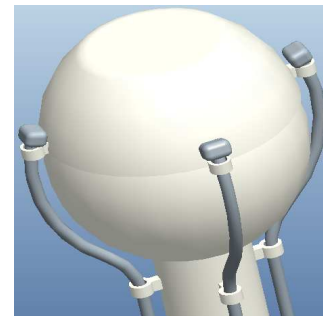


Fig. 1 Pro-E Model of the modified Ball & Socket Joint

S. Ahmad is with Department of Mechatronics, National University of Sciences and Technology, Pakistan (e-mail: samitariq86@yahoo.com).

A. Masood is with Department of Mechatronics, National University of Sciences and Technology, Pakistan (e-mail: am34029@yahoo.com).

U. S. Khan is with Department of Mechatronics, National University of Sciences and Technology, Pakistan (e-mail: umarshahbaz@gmail.com).

The size of the wrist actuator is also a consideration in the design process and for that matter salient data has been collected for the average size of the wrist joint [8].

TABLE I
 CHARACTERISTICS OF RIGHT HUMAN FOREARM

Forearm Characteristics	Average
Forearm Circumference	28.48(cm)
Wrist Circumference	17.15(cm)
Wrist Breadth	6.02(cm)
Forearm Weight	1113.2(gm)

Considering the data, the diameter of the ball of the joint is set at 4cm and the socket covering it makes the diameter 5cm.

III. MATERIAL SELECTION

The wrist actuator needs to be light in weight but it should be hard enough to with stand the wear and tear common to prosthetic actuators. Also the friction coefficient of the material should be such that it can be easily used for the Ball & Socket joint. If the friction coefficient of the material will be high then majority of the force produced by the motors will be utilized in overcoming it and the wear and tear of the actuator will also increase.

Some common materials for the production of the Ball & Socket joints are Steel, Brass and Bronze. These materials have good wear resistance and with proper polishing and greasing provide a very low friction coefficient but the major drawback is the weight.

These materials have high density that makes them heavy that can increase the weight of the actuator greater than the average weight of the human forearm (Refer to Table I). Another choice of the material can be Aluminum that is lighter in weight than the materials discussed before, but the drawback of Aluminum is that under high load or after long use it starts to become sticky and loses its low frictional properties. Properties of some plausible materials for making a Ball & Socket joint are given in Tables 2 & 3 [9], [10], [11].

The collected data suggests that PolyTetraFluoroEthylene (PTFE) is the material of choice as it is lighter in weight and has low friction coefficient. The Hardness number of PTFE is also low but the low friction ensures that Ball & Socket joint created with PTFE will be subjected to less wear and tear which allows us to utilize its other benefits. PTFE is also inert chemically and electrically which further makes it a good choice of material for use in prosthetic equipment.

TABLE II
 MECHANICAL PROPERTIES OF PLAUSIBLE MATERIALS

Material	Hardness (BN)	Density (g/m ³)
Aluminum	22-40	2.71
Austenitic Steels	192-210	7.88
Commercial Bronze	60-125	8.5
Aluminum Brass	70-175	8.6
PTFE	15	2.0-2.29

TABLE III
 FRICTION COEFFICIENTS OF PLAUSIBLE MATERIALS

Material 1	Material 2	Coefficient of Static Friction		Coefficient of Dynamic Friction	
		Static	Lubricated	Static	Lubricated
Aluminum	Aluminum	1.05	-	1.4	-
Mild Steel	Aluminum	0.61	-	0.47	-
Mild Steel	Mild Steel	0.74	-	0.57	0.09
Mild Steel	Cast iron	-	0.183	0.23	0.133
Hard Steel	Hard steel	0.78	0.11-0.23	0.42	0.03-0.19
Mild Steel	Brass	0.51	-	0.44	-
Cast iron	Bronze	-	-	0.22	0.077
Steel	PTFE	0.04	-	-	0.04
PTFE	PTFE	0.04	-	-	0.04

IV. TRANSMISSION

The technique utilized for the transmission of motor torque to the Ball & Socket joint closely resembles the natural force transmission technique of the human body. The human body applies force through muscles that can only apply unidirectional force i.e. the retraction force and not the extension force. Another feature is that the muscles are arranged in a parallel manner due to which when one muscle retracts the one parallel to it extends but the extension force is not from the muscle it self but is caused by the other muscle that is contracting. The Fig. 2 shows the arrangement of muscles in the upper body of a human being.

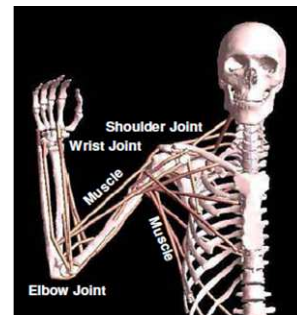


Fig. 2 Human arm's muscle drive scheme [12]

The transmission technique of the proposed actuator uses the flexible Bowden cables arranged in a manner similar to the human body. Two Bowden cables have been used in the proposed actuator and they are connected to two DC geared motors that provide the required torque. A major issue in designing a transmission using the flexible Bowden cables is to find the optimal number of cables and the optimal number of cable attachment points. This has been done by using two classical theorems in convex analysis that can be employed because of the cable's unilateral properties [13].

Caratheodory Theorem: If a set $X = \{v_1, v_2, \dots, v_k\}$ positively spans $_n$, then $k \geq n + 1$.

Steinitz Theorem: If $S \subset _n$, and $q \in \text{int}(\text{co } S)$, then there exists $X = \{v_1, v_2, \dots, v_k\} \subset S$ such that $q \in \text{int}(\text{co } X)$ and $k \leq 2n$.

The Caratheodory theorem gives the lower bound of the number of driving cable attachments required for positive cable tension in a parallel driven mechanism and with n -DOF's it is $n+1$. The Steinitz theorem gives the upper bound on the minimal number of driving cable attachments required to attain positive cable tension and for n -DOF's it is $2n$. Together the two theorems imply that the number of driving cable attachments for a parallel mechanism ranges from $n+1$ to $2n$. So in the design of the transmission of the actuator under consideration the number of DOFs are 2 which give the minimal number of driving cable attachments for positive cable tension to be 3 and the upper bound to be 4. In the design the number of cable attachments has been selected to be 4 so that only two motors are required to run the mechanism. This also allows us to use only two cables for the running of the mechanism.

As shown in Fig. 3, the two cables are attached at four points to the socket of the joint. These cables run around the pulleys attached to the motors and provide the required force for the movement of the mechanism.

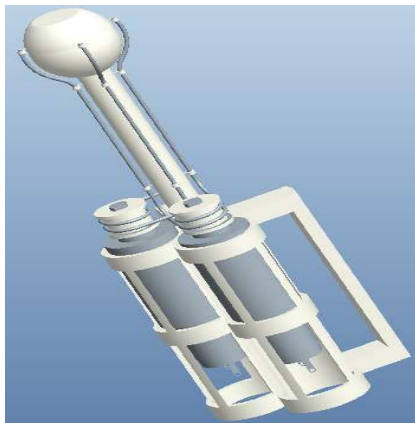


Fig. 3 Pro-E Model of Transmission of the Actuator

A. Bowden Cables

A Bowden cable is the union of a cable, acting as a tendon, and an elastic, flexible and low friction sheath acting as the synovial sheaths of human body. The construction of the Bowden cable is shown in Fig. 4.



Fig. 4 Construction of Bowden cable 1) plastic sheathing 2) outer sheathing made of spring steel wire 3) Teflon guide sleeve 4) spiral wire 5) inner core made of spring steel wire [14]

The cable is selected from the calculation of the amount of tensile strength that its spring steel wire rope can carry because the inner wire rope is the main component that carries the load and the other components are for the protection of the wire. To calculate the safe working load (SWL) of the wire rope the following formula is used [15], [16], [17].

$$D \times D \times 8 = \text{SWL (in tons)}$$

Where D is the diameter of the wire rope in inches

In the proposed actuator, to calculate the minimum diameter of wire rope that can be used first we have to find the amount of force that the wrist actuator will have to apply. Some data has been gathered on the amount of force an average human being applies from the wrist joint during the routine tasks of picking and placing of the objects. The mean value comes out to be 4Nm. The force is calculated by finding the distance of the point where the load has been applied to the center of the wrist joint.

$$\text{Torque, } \tau = \text{Force, } F \times \text{Moment arm, } r$$

The force comes out to be 80N if we have a moment arm of 50mm which is the average distance of the center of palm to the wrist center. In tons the value is 0.009. So the minimum diameter of wire rope that can be utilized by remaining in the safety limit is 0.0335inch or 0.8509mm. The wire being used in the designed actuator is 2mm thick so it's SWL is 0.05tons or 445.2N.

B. Motor Selection

The selection of the motor is governed by some design requirements. The first is that the motor should be able to apply the required torque. The second is the weight and size so that the two motors can be placed in the forearm and then can be easily lifted by the human user. The third requirement is that the motors should be DC motors so that they can be operated by the battery and the need of extra circuitry can be removed. The fourth and final requirement is that the price of the motor should be moderate so that the actuator can be affordable to common people.

Considering all of the above requirements a search has been carried out that resulted that a single motor that can fulfill all the requirements is not available and a trade off is inevitable. Among the requirements the most important are the first two because if they are not met the design of the actuator will have to be changed. So from the research for the suitable motor, three different motors have been selected. All the three have a planetary gear head that helps in increasing the torque output. Some specifications of the searched motors are shown in Table 4 [18], [19], [20].

TABLE IV
 DATA OF GEARED MOTORS

	ICH D323-3A	Faulhaber 2232S012BSL with Gearhead Series30/1S	Beetle B231 Part# 0-B231
Length(mm)	132.5	88	68.15
Diameter(mm)	32	30	21.8
Weight(g)	320	200	100
Rated Torque(Nm)	3.9	4.5	2.62
Rated Speed(rpm)	10	4000	70
Rated Current(A)	0.495	1.10	0.4
Voltage(V)	24	12	12

V. CHARACTERISTICS OF WRIST ACTUATOR

Some characteristics of the designed powered prosthetic wrist actuator are given in table 5 and the final Pro-E model is shown in Fig. 5.

TABLE V
CHARACTERISTICS OF WRIST ACTUATOR

Characteristics	Wrist Actuator
Actuator Forearm Circumference	28.274 (cm)
Actuator Wrist Circumference	14.76 (cm)
Actuator Wrist Breadth	4.7 (cm)
Actuator Weight	870 (gm)
Max. Lift Capacity	3.9 (Nm)
Flexion/Extension axis	85°/90°
Abduction/Adduction axis	15°/45°



Fig. 5 Pro-E Model of Powered Wrist Actuator with Forearm Casing

VI. CONCLUSION

The wrist actuator proposed in this paper is a novel design which is light in weight, low in price and is designed specifically to provide the degrees of rotation that the human wrist is able to produce because the previous designs by other researchers were only able to provide the required degrees of rotation in the Abduction/Adduction axis but not for the Flexion/Extension axis. The actuator also meets the requirements for a prosthetic limb and can be developed for practical implementation. This actuator can also be used in rehabilitation exoskeletons.

REFERENCES

- [1] DARPA RP 2009 robotic prosthetic arm, Available: www.vandorendesigns.com/RP2009p1.html
- [2] Peppino Tropea, Giovanni Stellin, IEEE Member, Maria Chiara Carrozza, IEEE Member, Paolo Dario, IEEE Fellow "Development of an innovative and compliant robotic wrist". Proceedings of the 2nd Biennial IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics Scottsdale, AZ, USA, October 19-22, 2008
- [3] Peter J. Kyberd, PhD; Edward D. Lemaire, PhD; Erik Scheme, MSc; Catherine MacPhail, BSc; Louis Goudreau, BAsC, PEng; Greg Bush, BA, CP(c); Marcus Brookesshaw, BSc "Two-degree-of-freedom powered prosthetic wrist". Journal of Rehabilitation Research & Development, Volume 48, number 6, 2011.
- [4] Weihai Chen, Quanzhu Chen, Jianbin Zhang, Shouqian Yu, "Forward Kinematics and Workspace Analysis for a 7-DOF Cable-Driven Humanoid Arm". Proceedings of the 2006 IEEE International Conference on Robotics and Biomimetics December 17 - 20, 2006, Kunming, China

- [5] igus® part no. AGRM-08, available: http://www.igus.com/wpck/default.aspx?PageName=igubal_Axialgelenk_AGRM&CL=US-en
- [6] RS stock no. 689-401, available: <http://in.rsdelivers.com/product/rs/ball-and-socket-joint-m6/0689401.aspx#>
- [7] Automation Components® R3494.L016, available: www.automationcomponents.co.uk/en/catalog/rotary/ball-socket-joints/other-ball-socket-parts/r3494
- [8] R.F. Chandler, C.E. Clauser, J.T. McConville, H.M. Reynolds and J.W. Young, "Investigation of the internal properties of the human body", report prepared for U.S Department of Transportation National Highway Traffic Safety Administration.
- [9] Norman A. Waterman and Michael F. Ashlay, "CRC-Elsevier Materials Selector (Vol.2)", CRC Press 2000.
- [10] Robert L. Norton, "Machine Design An Integrated Approach" second edition. Pearson Education, Inc
- [11] Polymer Data Handbook, Oxford University Press, Inc.
- [12] Guilin Yang, Wei Lin, Mustafa Shabbir Kurbanhusen, Cong Bang Pham, and Song Huat Yeo, "Kinematic Design of a 7-DOF Cable-Driven Humanoid Arm: a Solution-in-nature Approach" Proceedings of the 2005 IEEE/ASME International Conference on Advanced Intelligent Mechatronics Monterey, California, USA, 24-28 July, 2005
- [13] R. Murray, Z. Li, and S.S. Sastry, A Mathematical Introduction to Robotic Manipulation, CRC Press, 1994.
- [14] Construction of Bowden Cables, available: www.dt-germany.com/news/news-details/article/dtR-product-portrait112010
- [15] Safe Working Load of wire rope Formula, available: www.globalsecurity.org/military/library/policy/navy/nrtc/14251_ch5.pdf
- [16] Robert Scharff "Workshop Math". Sterling Publishing Company, Inc., 31-Dec-1989
- [17] Phil Croucher, "Operational Flying: A professional pilot's manual". Electrocutation Technical Publishers (December 2002)
- [18] BeetleB231 DC geared motor with Gearhead ratio 231:1, available: <http://www.robotcombat.com/products/0-B231.html>
- [19] Brushless DC servo motor 2232S012BSL with Planetary Gearhead Series 30/1S, available: http://www.faulhaber.com/uploadpk/EN_2232_BSL_MIN.pdf, http://www.faulhaber.com/uploadpk/EN_301S_MIN.pdf
- [20] ICH motion, D323-3A DC Planetary Gear Motor, available: [http://www.ichmo.com/Products/info/id/57/pid/183/l/en/D323-3A_\(Size_32mm\)/html](http://www.ichmo.com/Products/info/id/57/pid/183/l/en/D323-3A_(Size_32mm)/html)