KINEMATICS MODELING AND WORKSPACE ANALYSIS OF A CABLE-BASED PARALLEL MANIPULATOR FOR SHOULDER REHABILITATION

Wilgo Moreira Nunes, wilgomoreira@gmail.com
José Francisco Ribeiro, jribeiro@mecanica.ufu.br
João Carlos Mendes Carvalho, jcmendes@mecanica.ufu.br
Rogério Sales Gonçalves, rsgoncalves@mecanica.ufu.br
Federal University of Uberlândia, Uberlândia, Brazil

Abstract. *The science of rehabilitation showed, in most cases, that repeated movements of human members can to help the patient regain the functions of the member injury. Robots for these tasks can be more efficient in performing these exercises than humans. Robotic systems for rehabilitation can be generally used to record information like position, trajectory, force and velocity exploiting the motor performance during active movements, and to guide the movement of a patient limb attached to the device. The cable-based parallel manipulator consists of a moving platform, which can carry an end-effector, and a base. These two elements are connected by multiple cables that can extend or retract. These structures have characteristics that make them suitable for rehabilitation purposes like large workspace which may be adapted to different patient and different training, the mechanical structure is easy to assembly and disassembly and can be reconfigurated in order to perform different therapies, can be easy to transportation and have low cost and simple maintenance which are relevant characteristics for possible commercial system to be used by patients at home. This paper presents a cable-based parallel structure for rehabilitation of the movements of the human shoulder named CaMaReS (Cable Manipulator for Rehabilitation of Shoulder). The robotics structure consists of four cables that allow the shoulder movements with different limits of movement and speed. After kinematics modeling, the kinds of workspace are defined then a statically reachable combined workspace for different geometric structures of fixed and moving platform is obtained. This workspace is defined as the situations of reference point of the moving platform, center of mass, which under external forces the moving platform should be in static equilibrium under conditions that length of all cables must not be exceeded from the maximum value and all of cables must be at tension. The development of this robotic device is justified by the large number of people with shoulder problems like stroke, polio, arthritis and disaster recovery.*

Keywords*: rehabilitation, cable-based parallel manipulator, shoulder, workspace*

1. INTRODUCTION

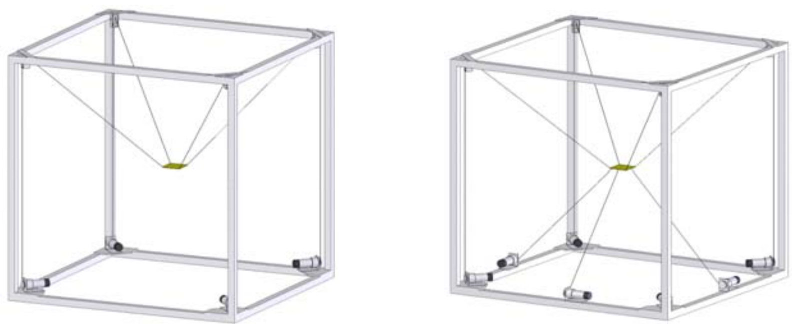
The science of rehabilitation showed in most cases that repeated movements of human members can to help the patient regain the functions of the member injury. Robots for these tasks can be more efficient in performing these exercises than humans. Robotic systems for rehabilitation can be generally used to record information like position, trajectory, force and velocity exploiting the motor performance during active movements, and to guide the movement of a patient limb attached to the device. All the data can be archived and then compared to check the progress of patients on therapy.

Different robotic architectures have been developed and applied in rehabilitation. The most successful example of a robot designed for neurorehabilitation is probably the MIT-Manus (Krebs *et al.*, 2004), developed at Massachusetts Institute of Technology (MIT). The MIT-Manus robot consists of two degrees of freedom serial robot that may influence or interact with the patient's arm over a working plan. Despite the effectiveness of the MIT-Manus has been proven by clinical trials this robot can't provide all types of motion required by conventional therapy, especially the outlaws of the plan, besides the high cost of U$ 60,000.

A three-dimensional workspace is usually obtained by serial robots with multiple degrees of freedom. Some examples are: ARM (Assisted Rehabilitation and Measurement), despite this robot allow three-dimensional movements its structure is heavy and the quality of movement is affected by the high inertia of the system (Kahn *et al.*, 2006); the MIME (Mirror-Image Movement Enabler) is a Puma robot model 562 with 6 degrees of freedom which is attached to the patient's arm by moving it into pre-trajectories programmed (Lum *et al.*, 2002) but due to its characteristic of producing high forces and speeds and to need an operator industrial robots this structure does not represent a viable tool for rehabilitation assistance, in addition to high cost; Armin is an exoskeleton with 6 degrees of freedom (Nef and Riener, 2005) that can be fixed around the patient's arm and provide all the physiotherapy movements, the main disadvantage of this robot is the complexity of adjusting the parameters of the arm for different patients and complex construction due to the high number of mechanical components; another robotic system applied to rehabilitation is REHAROB (Rehabilitation Robot), a robotic system based on two industrial robots from ABB (Fazekas *et al.*, 2007) that allow three-dimensional movements by moving the forearm and arm, but this system has disadvantages such as the inability to transport and the prohibitive cost around U$ 150,000.

These serial robots are heavy machines that are not easily transportable, have high prices, pose risks to patients with fractures, but their major drawback is the resistance of patients to use these systems. Due to the problems presented in the use of industrial robots in the treatment of rehabilitation, the cables-based parallel manipulators are an alternative.

The cable-based parallel manipulator consists of a moving platform, which can carry an end-effector and a base. These two elements are connected by multiple cables that can extend or retract, Fig. 1, (Hiller *et al.*, 2009). A cable-based manipulator can move the end-effector by changing the cables lengths while preventing any cables becoming slack. Therefore, feasible tasks are limited due to main static, or dynamic, characteristics of the cables because they can only pull the end-effector but do not push it (Cannella *et al.*, 2008).



(a) (b)

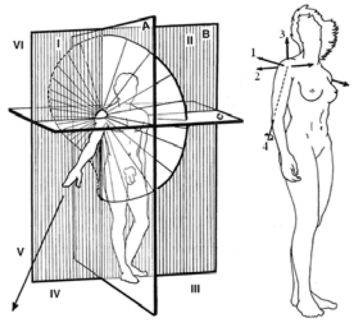
Figure 1.Types of cables-based parallel manipulators. (a) underconstrained; (b) fully-constrained (Cannella *et al.*, 2008).

These structures have characteristics that make them suitable for rehabilitation purposes. They have large workspace which may be adapted to different patient and different training. The mechanical structure is easy to assembly and disassembly and can be reconfigurated in order to perform different therapies and can be easy to transportation, the actuators are often located on the fixed base and the structure can be reconfigurated only by changing the actuators positions and/or the attachment points of the cables. The structures are modularity and have good inertial behavior as due to the fact that this kind of systems has small moving masses consisting of cables and end-effector. Such kinds of manipulators have low cost and simple maintenance which are relevant characteristics for possible commercial system to be used by patients at home. In the clinical point the use of cables instead to rigid links makes the patient fell less constrained and is important because it helps the acceptance of a new technology. These characteristic makes the cable-based parallel structures ideal for rehabilitation (Homma *et al.*, 2002). The drawbacks related to the use of cable-based parallel structure are the physical nature of cables that can only pull and not push and the workspace evaluation becomes forces dependent and can have a complex and irregular shape (Hiller *et al.*, 2009).

Some examples of these structures are described. The Calowi (Cassino Wire Low-cost robot) has architecture 4-4, four cables connected to the end-effector in four different transmission systems with pulleys. The cables are actuated by four DC motors which can extend and retract the cables. This structure is intended as low cost manufacturing applications with different purposes as: helping the elderly and patients with lower limb problems in operations to sit and get up; rescue in disaster areas, or transportation of persons in hospital rooms (Cannella *et al.*, 2008). Mayhew et al. (2005) developed the MACARM (Multi-Axis Cartesian-based Arm Rehabilitation Machine), a robot that is actuated by cables for rehabilitation of human upper limbs. The NeReBot (NeuroRehabilitation robot) have three degrees of freedom and is designed for rehabilitation of patients with upper limb problems. Its operating principle is simple: once the patient's forearm is fixed in splint (or orthosis) the machine can produce stimuli in the upper limbs by pulling three cables of nylon (Fanin *et al.*, 2003, Rosati *et al.*, 2005). MariBot (Marisa robot) is an evolution of NeReBot and have five degrees of freedom. It is a hybrid formed by a plan serial robot manipulator with 2 degrees of freedom used to position the cables on the plan, and a parallel structure actuated by cables with three degrees of freedom that allows the movements of the upper limb of patients in rehabilitation treatments (Rosati *et al.*, 2005).

2. SHOULDER MOVEMENTS

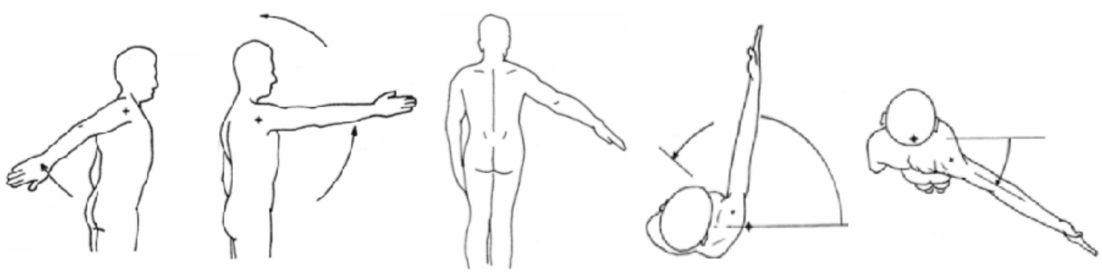
The shoulder is the proximal joint of the upper limb that has three degrees of freedom (Kapanji, 2000). It is the articulation of the human body that promotes the arm movements in the three planes of space: Plan A - Sagittal; Plan B - Front and Plan C - Horizontal, Fig. 2(a), in for three main axes: Cross Axis (1), anterior-posterior Axis (2) and Vertical Axis (3), Fig. 2(b).



(a) (b)

Figure 2. (a) Plans for analysis of shoulder movements; (b) axes of movement of shoulder (Kapanji, 2000).

The shoulder joint has the following movements: horizontal Flexion and Extension, Adduction/Abduction, vertical Flexion and Extension and Medial Rotation. A scheme for shoulder movements is shown in Fig. 3. The range shoulder are: vertical flexion 0° to 180°; vertical extension 0º to -45/-50°, abduction 0º to 180°; adduction 180° to 0º; horizontal flexion 0º to 140º and horizontal extension 0º to -30/-40° (Kapanji, 2000).



(a) (b) (c) (d) (e)

Figure 3. Shoulder movements. (a) Vertical Extension; (b) Vertical Flexion; (c) Abduction; (d) Horizontal Flexion; (e) Horizontal Extension (Kapanji, 2000).

3. KINETOSTATIC MODELING

The cable-based parallel manipulator 4-2, proposed in this paper, is formed by four cables arranged in a rigid structure (fixed platform) having two attachment points on the splint (moving platform), Fig. 4(a). The cables are represented by the lengths ρ_1, ρ_2, ρ_3 and ρ_4 and are connected to motors attached to pulleys at points P_1, P_2, P_3 and P_4 respectively. The points $v_1 = v_3$ and $v_2 = v_4$ correspond to the connection points of cables ρ_1, ρ_3, ρ_2 and ρ_4 in the splint respectively, Fig. 4(b). The distances between the points P_1 and P_2, V_1 and V_2 are adjustable depending on the size of the patient's arm. The cable-based parallel manipulator 4-2 allows three-dimensional motion of the arm from a desired trajectory. Figure 4(c) shows the prototype built at the Laboratory of Automation and Robotics at Federal University of Uberlândia. Figures 4(a) and 4(c) show the elements of the cable-based parallel manipulator 4-2, consisting of four sets formed by DC motor 24 volts and 45 Nm torque, encoder 500 pulses per revolution and pulley. In this first step toward implementation of graphic simulations and future experimental tests will be used a wooden puppet anthropometric from 1.80 m to simulate human body, Fig. (4c).

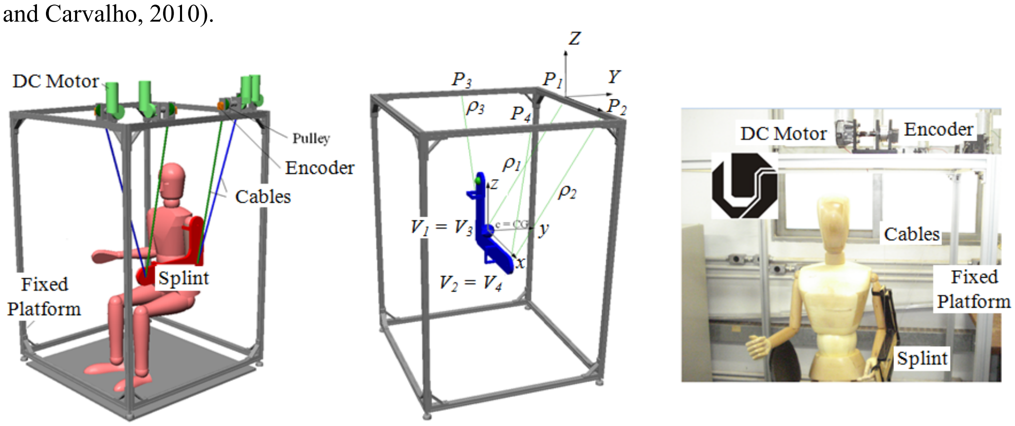
The kinematics model of cable-based parallel robots is obtained similarly to the model obtained from traditional parallel structures (Côté, 2003). The inverse kinematic problem consists in finding the cables lengths, ρ_i, as function of the end-effector pose. The forward kinematic problem consists of finding the end-effector poses for a given set of cables lengths ρ_i. For the kinematic model, the used parameters are shown in Fig. 4(b) and 5(a). The kinematic variables are the cables lengths ρ_i.

The inverse kinematic model of the proposed parallel structure 4-2 can be found by

$$
\begin{aligned}
\rho_i &= \left\| c + Q v_i - p_i \right\| \\
\rho_i^2 &= \left(c + Q v_i - p_i\right)^T \left(c + Q v_i - p_i\right) \\
\rho_i^2 &= c^T c + 2 c^T Q v_i - 2 c^T p_i + v_i^T v_i - 2 p_i^T Q v_i + p_i^T p_i
\end{aligned}
\quad (1)
$$

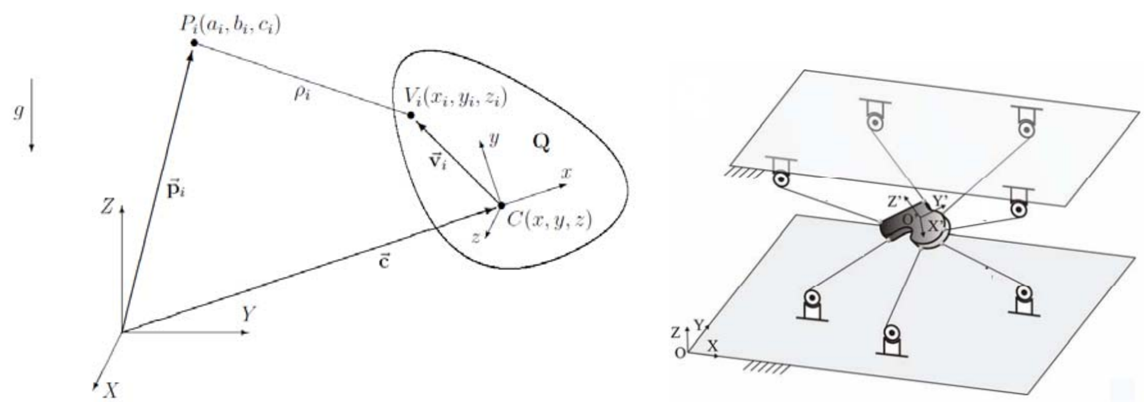
$$Q=\begin{bmatrix} \cos\beta\,\cos\gamma & -\cos\beta\sin\gamma & \sin\beta \\ \sin\theta\,\sin\beta\,\cos\gamma+\cos\theta\,\sin\gamma & -\sin\theta\,\sin\beta\,\sin\gamma+\cos\theta\,\cos\gamma & -\sin\theta\,\cos\beta \\ -\cos\theta\,\sin\beta\,\cos\gamma+\sin\theta\,\sin\gamma & \cos\theta\,\sin\beta\,\sin\gamma+\sin\theta\,\cos\gamma & \cos\theta\,\cos\beta \end{bmatrix} \tag{2}$$

With i varying from 1 to n (number of cables), where: p_i is the position vector of point P_i with components a_i, b_i and c_i in relation to fixed reference point, v_i is the position vector of point V_i with components x_i, y_i and z_i for the moving frame, C (c_x, c_y, c_z) is the position vector of center of gravity of the moving platform, Q is the rotation matrix between fixed and moving frame obtained by a rotation of θ about x-axis followed by a second rotation β about the new y-axis and a third rotation γ about the new z-axis and ρ_i is the distance between points P_i and V_i (cable length i) (Gonçalves and Carvalho, 2010).



(a) (b) (c)

Figure 4. (a) Scheme of the parallel structure 4-2; (b) Parameters of parallel structure 4-2; (c) Prototype built.



(a) (b)

Figure 5. (a) Kinematic variables (Côté, 2003); (b) A scheme for a cable-based parallel architecture (Ottaviano, 2007).

3.1. Static Force Analysis

The static force analysis is made considering that all cables must remain in tension under any load. When a manipulator performs a given task, the end-effector exerts force and moment on the external environment in the case of cable-based parallel structure forces are transmitted by extending and retracting cables and by ensuring the condition of pulling cables. The static force analysis is important in order to determine the quality of force transmission which is a fundamental aspect of the energetic efficiency of the manipulator and in the case of cable-based parallel structure is necessary to determination of the feasible workspace (Ottaviano, 2007).

As the speed of cable is low, in the proposed cable-based parallel manipulator 4-2, the analysis can be based on a static model of forces. In the Fig. 5(b) is shown how forces calculation is made for a general cable-based architecture with n cables, (Ottaviano, 2007).

The formulation of the equations is based on the use of unit vectors on the directions of the cables to the actuators. The sum of the forces (tensions of cables) is equal to the external forces acting on the system, the only external force acting is the weight of the arm with a splint. The same goes for the moments, the sum of moments is equal to the external moments applied to the system. The Equations (3) and (4) describe the model.

$$\sum_{i=1}^{n} F_i = \sum_{i=1}^{n} F_i \hat{\rho}_i = P \tag{3}$$

$$\sum_{i=1}^{n} t_i = \sum_{i=1}^{n} \hat{\rho}_i \times Qv_i = M \tag{4}$$

Writing in matrix form:

$$[J]^T [F] = [W] \tag{5}$$

The vector F contains the values of the tensions in the cables, which forces the actuator must exert. W is the vector with the values of forces and moments applied to the system, there is only a weight and external force acting on the mobile platform (splint). J is Jacobian matrix that represents the structure matrix. For the case of four cables presented in this paper, the Jacobian is written by Eq. (6).

$$J = \begin{bmatrix} \hat{\rho}_1 & \hat{\rho}_2 & \hat{\rho}_3 & \hat{\rho}_4 \\ \hat{\rho}_1 \times Qv_1 & \hat{\rho}_2 \times Qv_2 & \hat{\rho}_3 \times Qv_3 & \hat{\rho}_4 \times Qv_4 \end{bmatrix} \tag{6}$$

Equation (5) and (6) can be used to evaluate the cable tension for a given trajectory, together with the kinematics of the cable-based parallel architecture.

4. WORKSPACE

One of the most important characteristics of manipulators is the workspace. Workspace can be divided to different categories. Statically reachable combined workspace is on the main. This workspace is consist of poses of end-effector reference point (mass center) which under applied external forces such as weight and ignoring inertial effects, end-effector should be in static equilibrium, the length of all the cables be smaller than maximum amount and all the cables should be in tension (nonnegative stress) while rotation of the end-effector in some of the constant rotation angles of θ, β and γ is possible. Where the rotation angles θ, β and γ are rotation angles around fixed axes of moving platform X, Y and Z respectively, Fig. 4(b). In some cases we call this workspace the wrench feasible workspace. This workspace is consisting of all the poses of moving platform that we can apply a specific range of wrenches (forces and moments). Anyway this space can be divided in two categories; the first is constant orientation workspace and second is total orientation workspace. Constant orientation workspace is the one that mass center of moving platform can be available while orientation of end-effector should be possible in some constant orientation angles θ, β and γ. Total orientation workspace (sometimes called workspace dexterous) is consist of space in which mass center of moving platform can be available while orientation of end-effector should be possible in all constant orientation angles θ, β and γ. This workspace is a subset of constant orientation workspace (Hamedi and Zohoor, 2008).

In this section the statically reachable combined workspace, in cable-based robot proposed for shoulder rehabilitation are obtain. Because all the cables can sustain tension and cannot sustain pressure in all of moving platform positions, all the cables should have nonnegative tension. In addition are suppose all the cables are not elastic and they make a straight line between base joint and joint of moving platform, (Hamedi and Zohoor, 2008).

The initial workspace for the proposed structure is defined by movement circumduction. The movement circumduction reunites rotation for the three axes, Fig. 2(a). When this circumduction amplitude reaches its maximum, the arm in space describes an irregular cone: the cone circumduction. This cone delimits the sphere whose center is the shoulder and whose radius is the length of the upper limb, a spherical sector of accessibility, within which the hand can grasp objects without moving the trunk, eventually leads them to the mouth. In Fig. 2(a), the curve represents the base of the cone circumduction (trajectory of the fingertips), covering the different sectors of space determined by the planes of reference of the joint: A) Sagittal Plane (vertical flexion-extension); B) Frontal Plane (Abduction-Adduction); C) Horizontal Plane (Horizontal Flexion-Horizontal Extension). The curve passes (to the right upper limb) by sectors: III - below the front and the left; II - above, front and left; IV - above, behind and right; V - below, behind and right; VIII - below, behind and left a path is very short, because the extension-adduction amplitude is low, Fig. 2(a), the sector VIII is located below the plane C, behind the sector III and left the sector V. Sector VII is not visible, lies on top. Therefore, the study of the workspace will be based on the cone formed by the movement circumduction, Fig. 2(a).

Figure 6 shows the initial workspace for the structure developed, Fig. 4(c), taking into account the motion circumduction with limits of movements $\theta = 0^o$ to 180^o and $\beta = -50^o$ to 50^o.

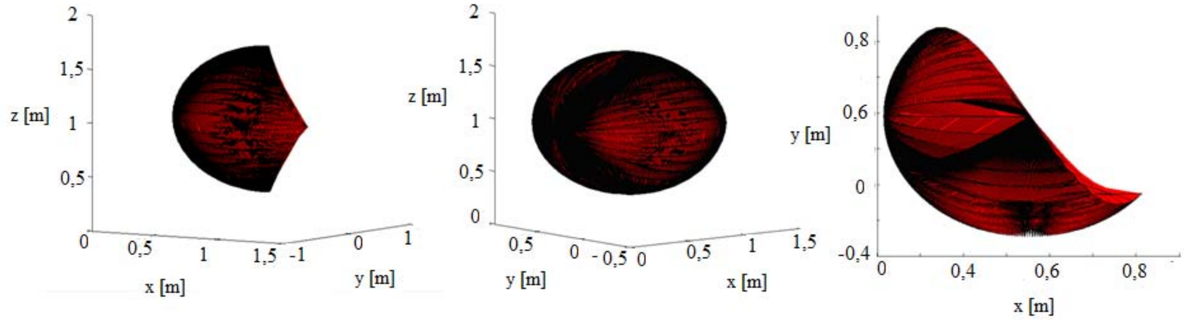


Figure 6. The initial workspace of cable-based parallel manipulator proposed. (a) Three-dimensional view; Perspective view; (c) Top view, units in [m].

A program was written by use of MATLAB software. This program checks all the points of search space for calculating the statically reachable combined workspace, with respect to range of search that is initial workspace, Fig. 6, consist of numerous number points and attain due search step and under following conditions:

$$[F]=[J]^{-T}[W] \qquad under\ \begin{vmatrix} F_i \in [F_{\min}, F_{\max}] \\ F_i > 0 \rightarrow i = 1,2,3,4 \\ l_i \le l_{\max} \end{vmatrix} \tag{7}$$

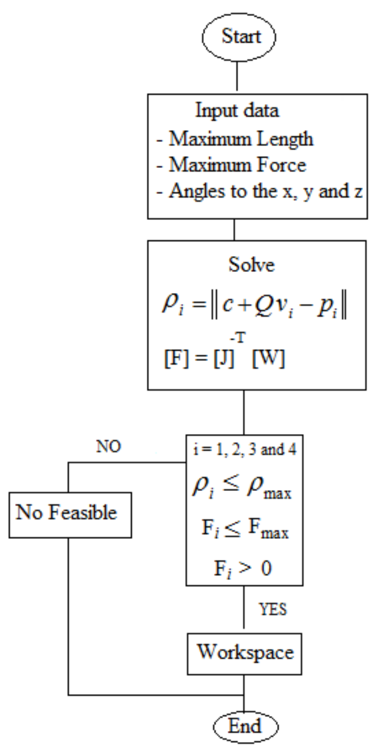
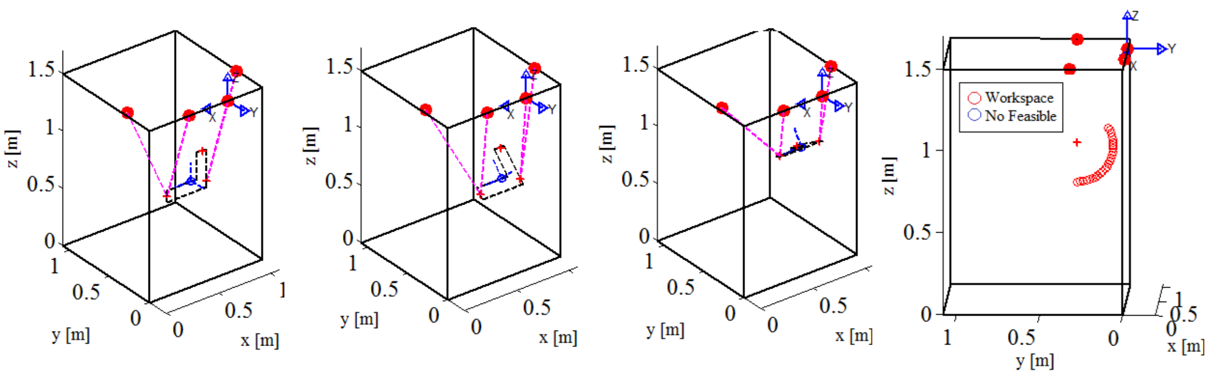


Figure 7. Algorithm for determining the statically reachable combined workspace.

4.1. Workspace for the shoulder movements physiotherapy

This section is to analyze the workspace of the various movements of shoulder physiotherapy from the proposed theory that defines the statically reachable combined workspace. There are some points that are possible, belong to the workspace, and others not possible. The algorithm for determining the statically reachable combined workspace is show in Fig. 7. The parameters used are: $F_{min} = 0.00001N$; $F_{max} = 400\ N$ (limit the resistance of nylon cable) and $l_{max} = 1,5\ m$.

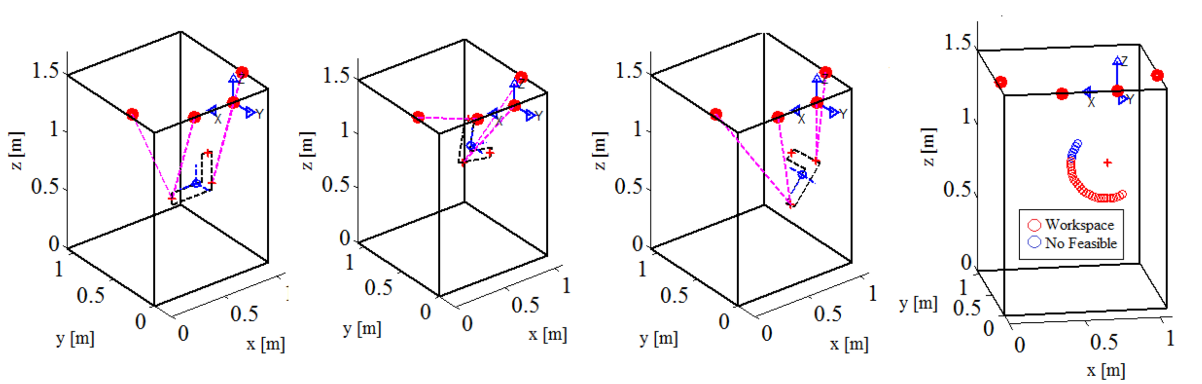
In the abduction movement, the angles around *y* and *z* axes are kept fixed, while the *x*-axis is rotated from 0° to 120° with increment of 5 degrees. Figure 8 shows the sequence of movement and the workspace obtained. The workspace in this movement has 25 possible points and zero points in the region no feasible.



(a) (b) (c) (d)

Figure 8. (a) Splint the initial position 0º; (b) Abduction 45º; (c) Abduction 120°; (d) Workspace.

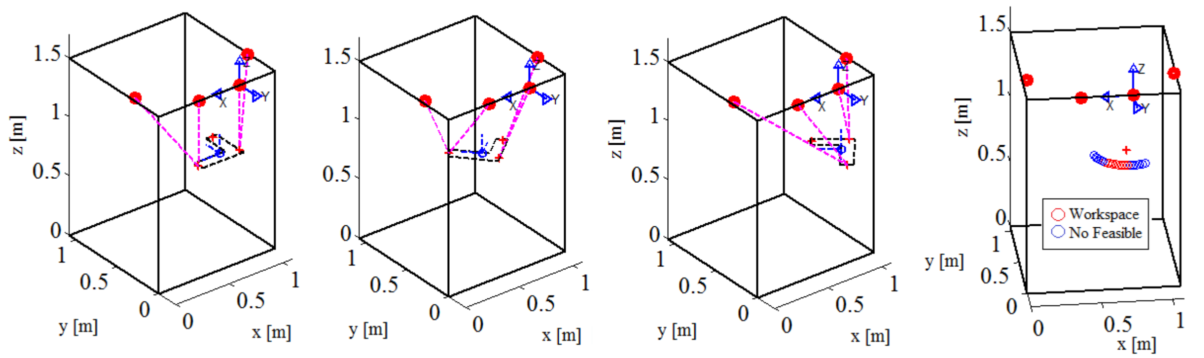
In the vertical movement of flexion and extension, the angles around *x* and *z* axes are kept fixed, while the *y*-axis is rotated from 50° to -100° with increment of 5 degrees. Figure 9 shows the movement together with your workspace. The workspace in this movement has 25 possible points and 6 points in the region is no feasible.



(a) (b) (c) (d)

Figure 9. (a) Splint the initial position 0º; (b) Vertical flexion 100º; (c) Vertical extension 50°; (d) Workspace.

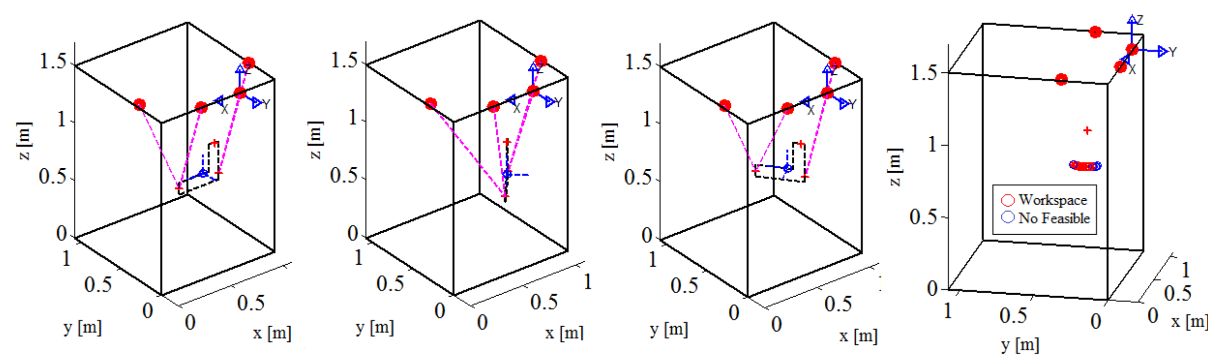
Horizontal movement of extension and flexion has the same characteristics as the previous movements, vertical flexion and vertical extension, the difference is in rotation around *y* occurs when the splint is rotated around *x* of the 90º with increment of 5º. Figure 10 shows the movement together with your workspace. The workspace in this movement has 9 possible points and 12 points in the region no feasible.



(a) (b) (c) (d)

Figure 10. (a) Splint the initial position 90º; (b) Horizontal flexion 50º; (c) Horizontal extension 50°; (d) Workspace.

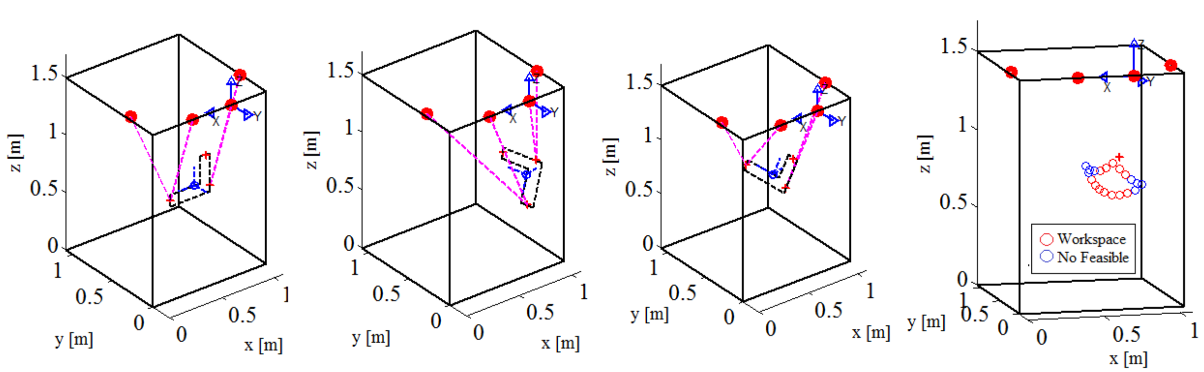
The movement of rotation around the *z* axis, keeping the *x* and *y* axis fixed is presented in Fig. 11. The movement is made from -50° to 50° with increment of 5º. The workspace in this movement has 15 possible points and 6 points in the region no feasible, Fig. 10(d).



(a) (b) (c) (d)

Figure 11. (a) Splint the initial position 0º; (b) Rotation in *z* 50º; (c) Rotation in *z* -50º; (d) Workspace.

In the combined motion of abduction-adduction with flexion-extension, this movement has rotation around the *x* and *y* axes simultaneously with *z*-axis fixed. Figure 12 shows the movement together with your workspace**.** The workspace in this movement has 12 possible points and 8 points in the region no feasible. Increasing the angle θ, 9º, and the angle β, 10º, are used.



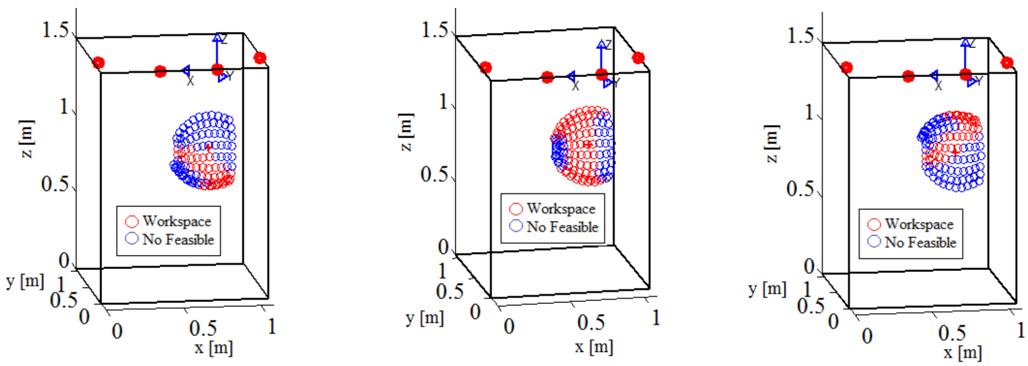
(a) (b) (c) (d)

Figure 12. (a) Splint the initial position 0º; (b) Rotation in *x* (45 º) and *y* (50º); (c) Rotation in *x* (45 º) and *y* (-50º); (d) Workspace.

4.2. Workspace from the limits of shoulder movement

The workspace more generally limited by the overall movement of the shoulder, as was done for the movement circumduction, Fig. 2, the patient's arm was stretched to determine any possible workspace measured at the tip of your finger, now in the new analysis, the arm is in position in the splint and the measurement is made at its center of gravity. The rotation around *z* also be considered because it affects both the force as the length of the cable. The idea is to determine the workspace most general possible. The limits of movements $\theta = 0^o$ to 180^o *(x)*, $\beta = -50^o$ to 50^o *(y)* and $\gamma = -50^o$ to 50^o *(z)*. Increasing the angle θ (18º) and the angle β (10º) are used.

Figure 13 shows some of the workspace obtained with different angles at *z*. In Fig. 13(a) the workspace has 38 possible points and 72 points in the region no feasible, Fig 13(b) the workspace has 64 possible points and 46 points in the region no feasible and in Fig 13(c) the workspace has 38 possible points and 72 points in the region no feasible.



(a) (b) (c)

Figure 13. (a) Workspace with γ = -50º (rotation *z*) constant; (b) Workspace with γ = 0º (rotation *z*) constant; (c) Workspace with γ = 50º (rotation *z*) constant

Finally, combining some rotations *γ*, form a single workspace, the increment used is 25º in *γ*. The workspace obtained is shown in Fig. 14(a). The workspace has 247 possible points and 303 points in the region no feasible. Graphically, it is possible to observe the configuration that gives more points for viable workspace, in Fig 14(b). The graph, the values near the *γ* = 0º shows more viable points for the workspace and *γ* = -50º or *γ* = 50º more points in the no feasible.

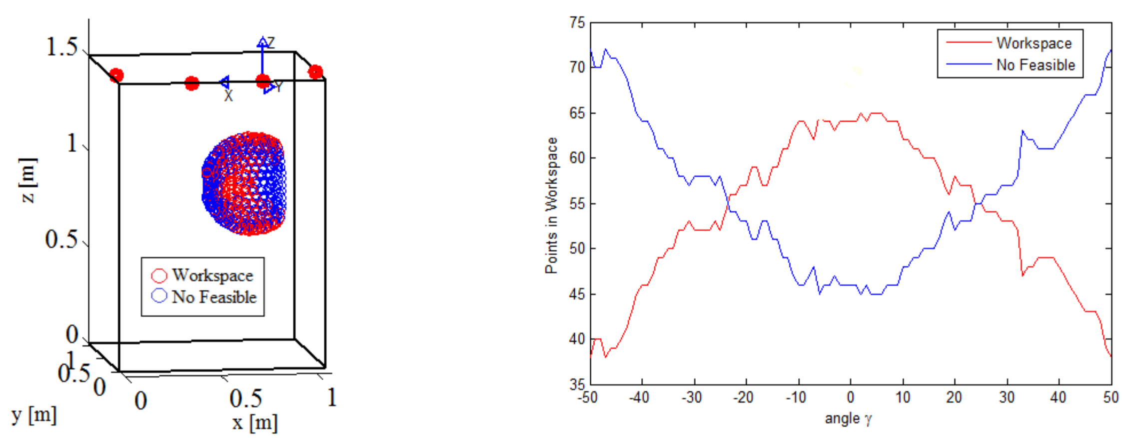


Figure 15. (a) Workspace with combination *γ* values; (b) Graphic with various angles *γ* and their respective points in the workspace.

5. CONCLUSION

The development of this robotic device is justified by the large number of people with shoulder problems. These problems are due of stroke, polio, arthritis, disaster recovery and can be applied to movements of physical therapy.

The developed cable-based parallel manipulator structure 4-2 is formed by four cables that connect the fixed platform and mobile platform (splint), allowing the realization of the major movements of the shoulder: vertical flexion-extension; abduction-adduction and horizontal flexion-extension. The Kinetostatic model was obtained for the proposed structure.

The movement therapy workspace and the motion limits were also analyzed, showing the regions viable or not. Graphically, it is possible to observe the configuration that gives more points for viable, values near the $\gamma = 0$ shows more viable points for the workspace and $\gamma = -50^o$ or $\gamma = 50^o$ more points in the no feasible.

The control system and experimental tests are in progress.

6. ACKNOWLEDGEMENTS

The authors are thankful to CNPq (process 471968/2009-9), PROPP/UFU, CAPES and FAPEMIG for the partial financing support of this research work.

7. REFERENCES

Côté, G., 2003, “Analyse et Conception de Mécanismes Parallèles Actonnés par Câbles”, Dissertation (in French).

Cannella, G., Ottaviano, E., Castelli, G., 2008, “A Cable-Based System for Aiding Elderly People in Sit to Stand Transfer”, MUSME 2008, The International Symposium on Multibody Systems and Mechatronics, San Juan (Argentina), 8-12.

Fazekas, G., Horvath, M., Troznai, T., Toth, A., 2007, “Robot-Medated Upper Limb Physiotherapy for Patients with Spastic Hemiparesis: A preliminary Study”, Journal of Rehabil Med, V. 39, p. 580-582.

Gonçalves, R. S., Carvalho, J. C. M., 2010, “Desenvolvimento de uma Estrutura Robótica Paralela Atuada por Cabos para Reabilitação dos Movimentos do Ombro”. In: VI Congresso Nacional de Engenharia Mecânica, 2010, Campina Grande, PB.

Hamedi J., Zohoor H., “Kinematic Modeling and Workspace Analysis of a Spartial Cable Suspended Robots as Incompletely Restrained Positioning Mechanism”. World Academy of Science, Engineering and Technology: Mechanical and Aerospace Engineering 2:2 2008.

Hiller, M., Hirsch, K., Bruckmann, T., Brandt, T., Schramm, D., 2009, “Common Aspects in Methods for the Design of Mechatronic Systems - Applications in Automotive and Robotic Systems U. of Duisburg-Essen”, Germany, XII International Symposium on Dynamic Problems of Mechanics, Angra dos Reis, RJ.

Homma, K., Fukuda, O., Nagata, Y. , 2002, “Study of a wire-driven leg rehabilitation system”, in Proceedings of the IEEE International Conference on Intelligent Robots and Systems, vol. 2, Lausanne, Switzerland, pp. 1451–1456.

Kahn, L. E., Zygman, M. L., Rymer, W. Z., Reinkensmeyer, D. J., 2006, “Robot-assisted reaching exercise promotes arm movement recovery in chronic hemiparetic stroke: a randomized controlled pilot study”, Journal of NeuroEngineering and Rehabilitation, pp. 1-13.

Kapandji, A. I, 2000, “Fisiologia Articular – Membro Superior”, 5ª edition, Editorial Médica Panamericana.

Krebs, H. I., Finley, M. A., Dipietro, L., OhlhofF, J., Whitall, J., Bever, C. T., 2004, “Does MIT-MANUS Upper Extremity Robot Testing Create a Learning Effect in Healthy Adults?”.

Lum, P.S., Burgar, C.G., Shor, P.C., Majmundar, M., Van der Loos, M., 2002, “Robot assisted movement training compared with conventional therapy techniques for the rehabilitation of upper-limb motor function after stroke”. Archives of Physical Medicine & Rehabilitation, 83(7):952-959.

Nef, T., Riener, R., 2005, “ARMin: Design of a novel arm rehabilitation robot”, in Proc. IEEE 9th Int. Conf. Rehabilitation Robotics ICORR2005, Chicago, IL, Jun. 2005, pp. 57–60.

Ottaviano E., A System for Tension Monitoring in Cable-Based Parallel Architectures, 12th IFToMM World Congress, Besançon (France), June 2007, University Cassino, Italy

Rosati, G., Gallina, P., Masiero, S., Rossi, A. , 2005, “Design of a new 5 d.o.f. wire-based robot for rehabilitation”, Proceedings of the 2005 IEEE 9th International Conference on Rehabilitation Robotics, Chicago, USA

8. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.