Development of Navi-Robot, a New Assistant for the Orthopaedic Surgical Room

D. Moschella[a1], G. Gatti[2], F.I. Cosco[a3], E. Aulicino [a4], P. Nudo [a5] and G.A. Danieli[6]

Dipartimento di Meccanica, Università della Calabria – Arcavacata di Rende (CS)
[a] Calabrian High Tech S.r.l. – Arcavacata di Rende (CS)
ITALY

Abstract — *This paper presents the concept of Navi-Robot, an integrated system of a navigator and a robotic arm for orthopaedic surgical procedures. Navi-Robot is a self-balancing 6 degrees of freedom (DOF) arm capable to switch between the navigation mode and robotic mode. The first mode is used detect bones' and articulations' features and positions, while the second mode is effectively used for surgical operations. The transition from the passive to the active mode is achieved by adopting special electrically activated brakes, which are also used to 'freeze' each arm in the desired configuration, for convenient use. A first prototype has been assembled and a basic electronics and control system have been implemented to perform kinematic tests. More specifically, from the kinematic and mechanical point of view, the whole system is actually consisting of three 6-DOF arms, two of which are mere navigation systems and the third is the actual Navi-Robot system, as defined above. The self-balancing feature of each arm is achieved by integrating the kinematic chain with a first four-bar-linkage, which guaranties full weight compensation. In a typical surgical procedure, the end effectors of the two navigation arms are fixed to bones of the joint of interest (JOI) and used to give a reference to the Navi-Robot for intervention. Patent applications cover the entire system.*

Keywords: Medical Robot – Navigators – Computer Aided Orthopaedic Surgery

I. Introduction

Computer-Assisted-Orthopaedic-Surgery (CAOS) [1-6] and Robotic-Assisted-Orthopaedic-Surgery (RAOS) [7-10] have been proposed and effectively adopted, in the last decades, to accommodate for the need of more and more precise and reliable surgical procedures, especially in the case of prosthetic implants. CAOS devices, such as navigation systems or navigators, have another important advantage as to reduce surgical teams' radiation absorption by using a Virtual Reality representation of the surgical theatre. On the other hand, these systems, do not supply any effective or physical support to the intervention. Thus, in any event, the doctor has to perform every surgical operation, such as positioning the surgical tool, moving bones accordingly to facilitate operation, and operating. From a mechanical point of view, all these procedures involve moving a rigid body in space.

In order to provide a more effective assistance, more recently [11], navigators and *cutting masks* have been used in synergy to correctly guide surgical cuts during prosthesis implants. However, also in this case, it is the doctor who is responsible to find the proper location for the mask, and since a unique mask is needed for each implant, the whole procedure's flexibility is compromised.

To overcome some of those problems, surgical robots have been proposed which, on the basis of pre-operative planning [12-15], replace the doctor when performing some particular operation, e.g. surgical cuts, embossing preparation, prosthesis installation. A better approach was followed by the Imperial College researchers, who proposed ACROBOT [16-19], which, by means of active constraints, guides the doctor opposing resistance when moving out of the correct region of operation, as planned before intervention. This method has the disadvantages of giving the doctor the whole responsibility for the precision of the operation.

Recently, Wahrburg *et al*.[20] combined a Navigator and a Robot as a surgical assistant able to correctly position a cutting mask for intervention.

In any case, the use of a conventional navigators does not account for the free-motion of the JOI , which may involve a continuous update of the actual JOI location.

The needs of orthopaedic surgery and the limitations of the actual systems (some of which has been reported about) have led the authors to the idea which is to be conceptually described in this work. The concept of Navi-Robot came up from the points mentioned above and from the authors' opinion that an equipment should never entirely replace a doctor, who solely has the expertise and sensitivity to recognize if a given operation, as preliminarily planned [21-22], is really to be performed that way.

[1] E-mail: mosdem@gmail.it
[2] E-mail: g.gatti@unical.it
[3] E-mail: francesco.cosco@unical.it
[4] E-mail: edoauli@alice.it
[5] E-mail: paola.nudo@unical.it
[6] E-mail: danieli@unical.it

II. Kinematic Configuration

The actual system is the development of the ‘Unical Goniometer’ [23-25], which was first used at the University of Calabria for different applications [24,26,27] and patents [28,29] cover some of them. More recently, the concept of Navi-Robot has been also introduced in [30] and [31].

The 6-DOF robotic arm described in this work is a hybrid parallel/serial kinematic structure with rotational transducers to measure the relative angle between consecutive linkages. The actual system is shown in Figure 1.

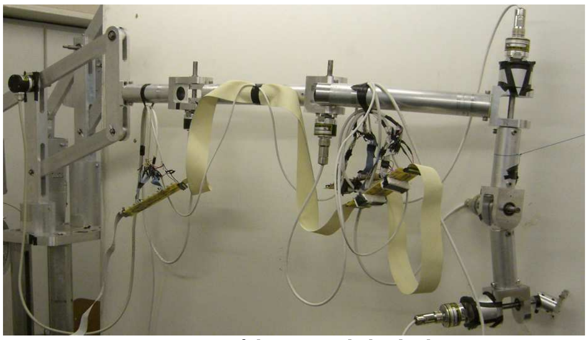

Figure 1. Picture of the 6-DOF hybrid robotic arm

It consists of a four-bar-linkage at the beginning of the kinematic chain, which gives a single translational degree of freedom, while a 5-DOF elbow structure is attached to the rod of the four-bar-linkage.

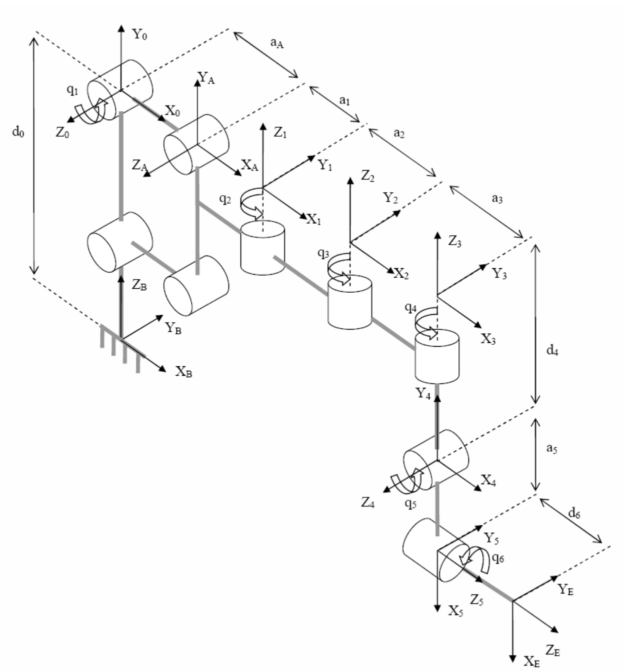

Figure 2. Scheme of the 6-DOF robotic arm

A schematic view of the 6-DOF arm’s structure, with embedded frames according to the Denavit-Hartenberg (D-H) convention [32], is shown in Figure 2 in its zero reference configuration and its kinematic model is readily to be defined below.

The first step to kinematic modelling is to assign a proper coordinate frame to each link. For a 6-DOF robotic system, joints and moving linkages are numbered from 1 to 6 starting from the base, which is referred to as link 0. A coordinate system $\{i\text{-}1\}$, $i = 1 \cdots 6$ is attached to the corresponding link. Coordinate systems are orthogonal and the axes obey the right-hand rule. Reference frame $\{B\}$ is the base frame with respect to which measurements are taken, reference frame $\{0\}$ is also fixed to the base and is used to accommodate for D-H convention, reference frame $\{A\}$ is an auxiliary frame attached to the upper crank of the four-bar-linkage, reference frame $\{i\}$, $i = 1 \cdots 5$ is attached to each moving link of the open-chain structure, and reference frame $\{E\}$ is the end effector frame with its origin on the endpoint location.

The kinematic equation of the robot arm is obtained by consecutive homogeneous transformations [32] from the base frame to the last frame, as

$$\mathbf{T}_E^B = \mathbf{T}_0^B \cdot \mathbf{T}_A^0 \cdot \mathbf{T}_1^A \cdot \prod_{i=2}^{5} \mathbf{T}_i^{i-1} \cdot \mathbf{T}_E^5$$

where $\mathbf{T}_0^B$ is the transformation matrix describing the pose of frame $\{0\}$ with respect to frame $\{B\}$, $\mathbf{T}_A^0$ is the transformation matrix describing the pose of frame $\{A\}$ with respect to frame $\{0\}$, $\mathbf{T}_1^A$ is the transformation matrix describing the pose of frame $\{1\}$ with respect to frame $\{A\}$, $\mathbf{T}_i^{i-1}$ $i = 1 \cdots 5$ are the transformation matrices from frame $\{i\text{-}1\}$ to frame $\{i\}$ and $\mathbf{T}_E^5$ is the transformation matrix describing the pose of the end effector frame $\{E\}$ with respect to frame $\{5\}$.

Each transformation matrix is a function of the corresponding joint variable q_i and of a set of kinematic parameters describing the link’s shape. With reference to Figure 2, transformation matrices are defined in the following form, according to [32]

$$\mathbf{T}_k^j = Rot(z, \theta_k) \cdot Trans(z, d_k) \cdot Trans(x, a_k) \cdot Rot(x, \alpha_k)$$

where $\mathbf{T}_k^j$ is a generic transformation from reference frame $\{j\}$ to $\{k\}$, *Trans()* and *Rot()* are the homogeneous translational and rotational matrix, respectively, and $\theta_k, d_k, a_k, \alpha_k$ are the D-H parameters, which are listed in Table 1.

$\mathbf{T}_k^j$	θ_k	d_k	a_k	α_k
$\mathbf{T}_0^B$	0°	670 mm	0 mm	90°
$\mathbf{T}_A^0$	q_1	0 mm	400 mm	0°
$\mathbf{T}_1^A$	- q_1	0 mm	300 mm	-90°
$\mathbf{T}_2^1$	q_2	0 mm	470 mm	0°
$\mathbf{T}_3^2$	q_3	0 mm	470 mm	0°
$\mathbf{T}_4^3$	q_4	100 mm	0 mm	90°
$\mathbf{T}_5^4$	q_5 -90°	0 mm	250 mm	-90°
$\mathbf{T}_E^5$	q_6	60 mm	0 mm	0°

TABLE I. D-H parameters of the actual arm

III. Kinematic Performance

Using the kinematic parameters listed in Table 1, the workspace of each arm has been computed to be an approximate 400x400x400 mm^3 box.

Kinematic performance of the system in terms of the theoretical resolution is evaluated when 16bit encoders are used as revolute joint sensors. Resolution [33] is defined the smallest incremental movement of which the robot end effector is capable of sensing. Resolution is a theoretical characteristic and may be evaluated given the configuration and the nominal dimensions of the linkage. It is affected by the individual encoders' resolution and depends on the instantaneous arm configuration. An approximate relation which gives an estimate of the arm's resolution may be given as follows

$$RS \approx \sum_{i=1}^{N} l_i(\mathbf{q}) \cdot \delta q_i \qquad (1)$$

where δq_i is the ith transducer resolution, $\mathbf{q} = [q_1, q_2, q_3, q_4, q_5, q_6]^T$ is the vector of joints' angles and l_i is the distance between the end effector endpoint and the revolute/prismatic axis of the ith joint. Since the endpoint displacement, resulting from the smallest incremental motion of the joints, varies significantly throughout the workspace, Eq. (1) is practically used for some particular system's configuration where l_i may be easily evaluated, e.g. in the zero reference configuration. In such a reference configuration, as shown in Fig. 2, Eq. (1) gives an estimate of the theoretical maximum resolution for the end effector endpoint. In that case, expressions for distances l_i in Eq. (1) are given as

$$l_1 = \sqrt{(a_A + a_1 + a_2 + a_3 + d_6)^2 + (d_4 + a_5)^2}$$
$$l_2 = a_2 + a_3 + d_6$$
$$l_3 = a_3 + d_6$$
$$l_4 = d_6$$
$$l_5 = \sqrt{a_5^2 + d_6^2}$$
$$l_6 = 0$$

Hence, when adopting 16bit encoders' with a resolution of about 0.0055 degrees per step, Eq. (1) gives $RS_{\max} \approx 0.343mm$. An average value for the theoretical resolution in the whole workspace is then evaluated, through simulations, giving a mean value of about 0.2 mm. This is quite a good theoretical performance, since common navigators' values are about 0.5 mm.

IV. Self-Balancing System

The self-balancing characteristic of the arm is achieved by using a counter-balancing weight as depicted in Figure 3, which shows a side view of the four-bar-linkage of the robotic structure. The open-chain part of the structure is not represented for clarity of representation. The black spot in Figure 3 represents the location of the centre of gravity of the structure, which varies according to the arm's configuration and thus depends on the joints' angles. By applying the virtual work principle for a virtual displacement δq_1 gives

$$F \cdot \delta l_1 - P \cdot \delta l_2 = 0$$

which can be manipulated to give

$$F = P \cdot \frac{a_A}{b_A}$$

where P is the structure's weight and F is the counter-balancing weight, which does not depend on the actual location of the centre of gravity of the arm.

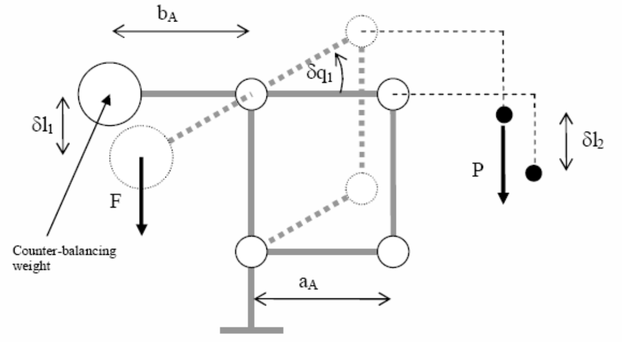

Figure 3. Scheme of the self-balancing system

Figure 4 shows a virtual representation of the whole three-arms system with connected a CAD model of the knee articulation, while Figure 5 shows a picture of the prototype with connected a workshop leg system (MITA Endo Leg, Medical Models Ltd, UK), which replicates the human knee anatomy and kinematics.

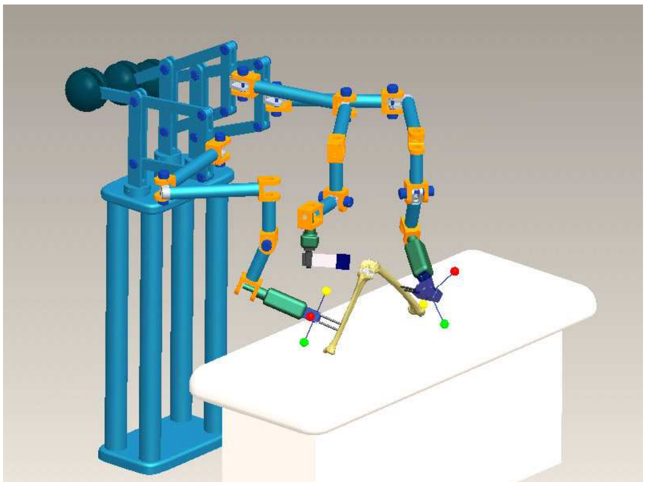

Figure 4. Virtual representation of the whole system

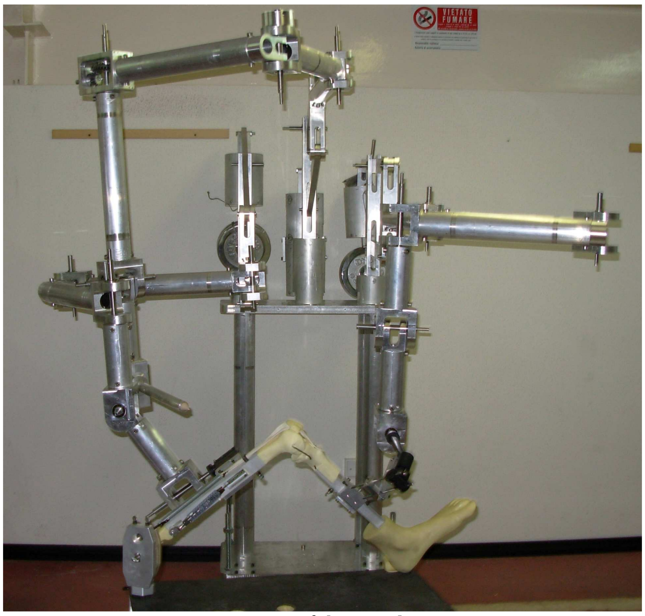

Figure 5. Picture of the actual prototype

V. Arm's Joints and Blocking-Brakes

Each joint of the passive arms is characterized by the presence of a blocking-brake, those enable the arm to be 'frozen' in a desired configuration. This allows, for instance, to fix the position and orientation in space of the JOI, to practically perform a surgical operation. Each joint of the active arm, i.e. the actual Navi-Robot, consists of a pair of blocking-brakes, one of which has the same functionality as for the passive arm, while the other is used to switch between the active/passive mode, by connecting or disconnecting the each actuator to the corresponding link. Therefore, for Navi-Robot, when both brakes of each joint are not active, the arm is passive and can be manually moved as a third navigator; when the first brake is activated, the arm configuration is 'frozen'; when the second brake is activated, the arm is active and enters the Robot mode.

The blocking-brakes are actuated by electric motors through a worm screw-driven slider (a) and two cam-leveraged elements (b), as indicated in Figure 6. They basically derive from a common drum brake, which has been modified and designed to exploit the self-amplification braking effect. Patent also covers this component's development [28].

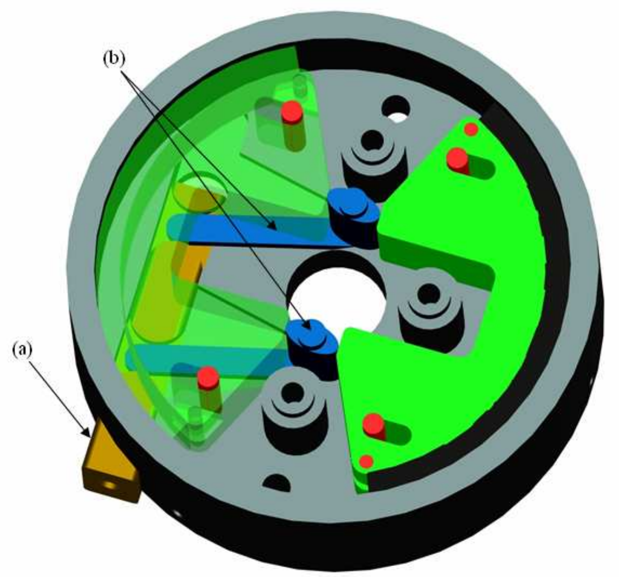

Fig. 6 – Actual blocking-brake configuration

Common brakes' systems are designed in either *duplex* or *simplex* configuration [34]. In the first configuration, both brake-shoes are hinged in an asymmetric way so as to brake most effectively only in one rotational direction. In the second configuration, brake-shoes' hinges are located symmetrically so as to brake in either rotational directions, but thus limiting the braking effectiveness compared to the *duplex* configuration.

The basic idea of the actual blocking-brake is to combine the advantages of either configurations by using two movable 'pivots' for each brake-shoe, so as to have a floating shoe. Those 'pivots' are, in fact, obtained as the contact points between the brake-shoe and a pair of disk cams, as depicted in the virtual prototype of Figure 6. Experimental tests and validation of such a component's performance are being part of further and deeper investigation.

VI. Discussion and Conclusions

This paper presents a preliminary design and a prototype of a novel surgical assistant, which combines, in a unique structure, a navigator and a robotic system. This is given the name of 'Navi-Robot' and it is mainly conceived to be used for orthopaedic procedures, where some applications have been reported.

In a typical application, three arms are to be used. Two of them are used as navigators and must be fixed to either bones of the articular joint of interest. The third, namely the Navi-Robot, is used either as a navigator/measuring device or as an active surgical robot.

The structure of each arm is designed as a hybrid parallel/serial kinematic chain. The parallel part is, in fact, a four-bar-linkage and it is adopted for an easy weight balancing. The serial part is designed as an elbow structure to give the end effector the remaining last five degrees of freedom. A kinematic model of the arm is derived using a standard and well-defined modelling convention. Kinematic parameters are chosen with regard to the actual application and considering an appropriate working space.

The theoretical resolution of the robotic arm is estimated to be 0.196 mm, as an average value in the working volume, and joints' sensors resolution is selected so that such a performance be better than that of commonly used navigators (i.e. about 0.5 mm).

Some preliminary and qualitative information about the component which enables for the transition between the Robot mode and the Navigator mode, i.e. the blocking brake, is given.

A virtual prototype of the system is realized to assist the design phase and a preliminary prototype of the whole three-arms system is assembled.

Each arm has been calibrated to compensate for components' manufacturing errors and for assembling misalignments. The final accuracy of the structure, in the working space, has been measured to be 0.376 mm (as a mean value) and showed to be consistent but a bit worse than the theoretical expectation, which has been evaluated to be 0.203 mm, in the same workspace. This is probably due to elastic deformations and small clearances.

The actual works being in progress are focused on: (1) mechanical (kinematic and dynamic) optimization on the base of experimental test and data; (2) calibration issues, such as how temperature changes and variable loads affect the kinematic performance of the system; (3) development of a reliable electronic circuitry and control system; (4) safety issues and surgical specifications/requirements.

Acknowledgements

The work presented in this paper was supported by the Italian Ministry of Research under FIRB RBAU01W5SE.

The authors would like to greatly acknowledge Mr. Emiliano Vitelli, Mr. Roberto Fico and Mr. Albenzio Lecce of the "Calabrian High Tech s.r.l." for the support given to the design and manufacturing process, Dr. Francesco Colacino, Dr. Gionata Fragomeni and Dr. Domenico Mundo for their comments and occasional useful criticisms, and MD Ermenegildo Giuzio of the "Ospedale Civile di Rogliano" for his medical suggestions.

References

[1] H. Bathis, L. Perlick, M. Tingart, C. Luring, D. Zurakowski, J. Grifka, "Alignment in total knee arthroplasty. A comparison of computer-assisted surgery with the conventional technique" *J Bone Joint Surg Br.* 2004 Jul;86(5):682-7

[2] F. Gebhard, C. Krettek, T. Hufner, "Computer aided orthopedic surgery (CAOS) -- a rapidly evolving technology" *Injury.* 2004 Jun;35 Suppl 1:S-A1

[3] N. Sugano, "Computer-assisted orthopedic surgery" *J Orthop Sc*i. 2003;8(3):442-8

[4] D.M. Kahler "Image guidance: fluoroscopic navigation" *Clin Orthop Relat Res*. 2004 Apr;(421):70-6

[5] F. Langlotz, "Potential pitfalls of computer aided orthopedic surgery", *Injury*. 2004 Jun;35 Suppl 1:S-A17-23

[6] L.P. Nolte, T. Beutler, "Basic principles of CAOS", *Injury*. 2004 Jun;35 Suppl 1:S-A6-16

[7] K. Bouazza-Marouf, I. Browbank, J.R. Hewit, "Robot-assisted invasive orthopaedic surgery" *Mechatronics*, Volume: 6, Issue: 4, June, 1996, pp. 381- 397

[8] K. Bouazza-Marouf, I. Browbank, J.R. Hewit, "Robotic-assisted internal fixation of femoral fractures" *Proc. IMechE part H – Engng Med.* 209 (H1), 51-58 (1995)

[9] A. Adili, "Robot-assisted orthopedic surgery" *Semin Laparosc Surg. 2004* Jun;11(2):89-98

[10] P.Y. Zambelli, S.T. Dewarrat, C.H. Bregand, G.A. Marti, C.H. Baur, P.F. Leyvraz "Electro mechanical arm – An alternative to the classical opto-tracking system" *3rd Annual Meeting of CAOS – International – Proceedings* – Marbella (Spain) June 18-21 2003 p.412

[11] N. Confalonieri, "The Role of Computer Assisted Surgery for Hip and Knee", *Ist PRO.MI National Congress*, Monza, nov. 12-13, 2004

[12] R.H. Taylor, L. Joskowicz, B. Williamson, A. Guéziec, A. Kalvin, P. Kazanzides, R. Van Vorhis, J. Yao, Rajesh Kumar, A. Bzostek, A. Sahay, M. Börner and A. Lahmer, "Computer-integrated revision total hip replacement surgery: concept and preliminary results", Medical Image Analysis (1999) volume 3, number 3, pp 301–319 Oxford University Press

[13] W. Siebert, S. Mai , R. Kober , P.F.Heeckt, "Technique and first clinical results of robot-assisted total knee replacement", The Knee 9 (2002) 173–180

[14] M. Nogler, A. Polikeit, C. Wimmer, A. Breuckner, S.J. Ferguson, M. Krismer, "Primary stability of a ROBODOC_ implanted anatomical stemversus manual implantation", Clinical Biomechanics 19 (2004) 123–129

[15] T**.** Siebel, W. Kafer, "Clinical outcome following robotic assisted versus conventional total hip arthroplasty. A controlled and prospective study of seventy-one patients" Zeitschrift fur Orthopadie und Ihre Grenzgebiete, 143 (4): 391-398 Jul-Aug 2005

[16] B.L Davies, R.D. Hibberd, K.L., Fan, M., Jakopec, S.J. Harris, "ACROBOT-Using Robots and Surgeons synergistically in Knee Surgery", Proceedings ICAR'97, 8th International Conference on Advanced Robotics. pp.173-180. July 7-9,. Monterey, California USA., 1997

[17] M. Jakopec, F. R. y. Baena, S. J. Harris, P. Gomes, J. Cobb and B. L. Davies, "The "Hands-on" Orthopaedic Robot "Acrobot": Early Clinical Trials of Total Knee Replacement Surgery", IEEE Transactions on Robotics and Automation, Special Issue on Medical Robotics, 19(5), pp.902-911, 2003

[18] J. P. Cobb, J. Henckel, S. J. Harris, M. Jakopec, F. R. y. Baena, M. P. S. F. Gomes and B. L. Davies, "An Active Constraint Robot Improves Outcomes in Total Knee Arthroplasty », Computer

Assisted Orthopaedic Surgery, Third Annual Meeting of CAOS International, Marbella, Spain, 18-21 June, pp. 64-65, 2003

[19] J. Cobb, J. Henckel, P. Gomes, S. Harris, M. Jakopec, F. Rodriguez, A. Barrett, B. Davies, "Hands-on robotic unicompartmental knee replacement - A prospective, randomised controlled study of the Acrobot system", Journal of Bone and Joint Surgery-British Volume, 88B (2): 188-197 FEB 2006

[20] J. Wahrburg, I. Gross, P. Knappe, S. Pieck, S. Ku¨nzler, F. Kerschbaumer, "An interactive mechatronic assistance system to support surgical interventions", International Congress Series 1268 (2004) 431– 436

[21] A. Leardini, L. Rapagnà, A. Ensini, F. Catani, A. Cappello, "Computer-assisted preoperative planning of a novel design of total ankle replacement" *Computer Methods and Programs in Biomedicine*, Volume: 67, Issue: 3, March, 2002, pp. 231 – 243

[22] G. Voss, A. Bisler, U. Bockholt, W.K. Muller-Wittig, A. Schaffer, "ICAPS an integrative computer-assisted planning system for pedicle screw insertion" *Stud Health Technol Inform* 2001;81:561-3

[23] G. Danieli, G. Fragomeni, E. Giuzio, O. La Ferla, "The UNICAL Goniometer, a fundamental tool in computer aided fixation and virtual reality representation of the operatory theatre". In: Proceedings of the 5th International Symposium on Computer Assisted Orthopaedic Surgery. 2000, Davos, Swiss, p. 31.

[24] G.A. Danieli, G. Fragomeni, E. Giuzio." Using Enhanced Reality in fracture reduction through external fixation". In: Proceedings of ESDA 2000 Conference. 2000, Montreux, Swiss, pp. 125-129.

[25] G. Gatti, G. Fragomeni, e G.A. Danieli, "Theoretical Study and Design of a six Degrees of Freedom Measuring Device for Biomechanical Applications", *6th Biennial Conference on Engineering Systems Design and Analysis*, Istanbul, Turkey, july 8-11 2002, # ESDA2002/BIO-015

[26] G.A. Danieli, G. Fragomeni and E. Giuzio "Driving orthopaedic tools precisely in a given direction through a point under closed skin conditions", *Problems of Applied Mechanics*, No 2 (11), 2003, ISSN 1512-0740, pp.59-66

[27] G.A. Danieli, G. Gatti, D. Mundo and G. Fragomeni, "Geometric Synthesis of a Four-Bar-Linkage for Knee External Fixation", *Proceedings of CK2005, International Workshop on Computational Kinematics*, Cassino, May 6-9 2005

[28] G A. Danieli, "Measuring open kinematic chain able to turn into a positioning Robot", PCT/IT05/000487 del 08/08/2005, WO2006016391 A1 of February 16th 2006

[29] G.A. Danieli, G. Fragomeni, G. Gatti e D. Mundo "Navigator – Robot for Surgical Procedures", PCT/IT03/00322 del 27/05/2003, WO 03/4469/3 of December the 4th 2003, EP03730474.8

[30] G.A. Danieli, G. Fragomeni, G. Gatti, D. Moschella and D. Mundo "Introducing Navi – Robot, a novel instrument for surgical procedures" *International Congress on Computational Biomechanics*, Zaragozza, Sept. 23-26, 2003, Vol. 1, 125-129

[31] G.A. Danieli, G. Fragomeni, G. Gatti, A. Merola and D. Moschella, "Navi-Robot, a Navigator able to turn itself into a Robot to reach the correct position for a given task during Orthopaedic Surgical Procedures" WSEAS Transactions on Systems, No 7, Vol. 4, July 2005, ISSN 1109-2777, pp. 1037-1045

[32] J. Denavit and R.S. Hartenberg. "A kinematic notation for lower-pair mechanism based on matrices". ASME J. Appl. Mechan 1955; 77: 215-221.

[33] International Standard ISO 9283, Manipulating industrial robots: performance criteria and related test methods.

[34] R. Limpert , *Brake design and safety*, SAE International, 1992.