HYBRID METHODOLOGY FOR THE DIAGNOSIS OF A KNEE TUMOR PROSTHESIS

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ABSTRACT

In medical practice, it is common to find complex biological and engineering systems; which have multiple interactions with the environment and within themselves.

Systems engineering deals with the study and understanding of reality. In order to implement or optimize complex systems it takes a transdisciplinary approach in which it integrates several disciplines in a synergic way.

The concepts and methodologies of General Systems Theory may help medicine, to integrate social, psychological, economic, historical and anatomic factors causing a medical condition. If all factors are considered, it is possible to provide a complete treatment. Prosthetic systems used for the treatment of bone tumors are one example of complex systems. The systemic view helps identify the factors that cause unexpected behavior of the prosthesis, its subsystems changes and patient interaction with the prosthesis in daily life.

Bone tumors adversely affect the health and physical integrity of patients who suffer them and, in severe cases, threaten the life of the patient. The anatomical region most often affected is the knee (over 50% of cases). One of the treatments listed in this condition is surgical removal of the tumor followed by reconstruction site affected by arthrodesis.

Patients with arthrodesis can perform some demanding activities from the physical point of view (walking in uneven or slippery surfaces, up and down slopes, picking things up standing). However, they have limitations as to the function of the affected limb. Arthrodesis has the advantage of involving a lower cost and that it preserves the patient's anatomy, which is a better option from the emotional point of view.

The National Rehabilitation Institute (INR, for its Spanish acronym) is one of the National Institutes of Health of the Mexican Federal Government. The INR has its own design of spacer and intramedullary nail for knee arthrodesis. The implant consists of a solid intramedullary nail of Ti-6Al-4V medical grade alloy, which is inserted through the medullary canal of the femur and tibia, two pin blockers for the femur and two pins for the tibia, and a cylindrical spacer standing on the site of the knee.

Although the implant has been successful many times, the life of the implant is limited by pins loosening, which causes intense pain to the patients, negatively affecting their quality of life. This is because the loads on the pins are very high, so they sink into the

bone beneath them. The use of Finite Element Analysis has shown that the location of the pins over the resection site plays an important role in the way the loads are distributed throughout the implant and the size of the resection influences the loads occurring on the pins.

To achieve a comprehensive diagnosis of the prosthetic system various departments of the INR should work together: Bone Tumor Service, Biomechanics Laboratory and Quality of Life Department.

To integrate the worldview of these areas a hybrid methodology (soft and hard systems) is implemented by developing an experimental design that involves a larger number of variables than the analysis described above. The methodology of Checkland and the Cybernetics Model are applied in order to evaluate the performance of the prosthesis and how it impacts the quality of life of patients.

Keywords: Hybrid methodology, diagnosis, prosthesis.

INTRODUCTION

Bone tumors affect adversely the health and physical integrity of the patients who suffer them; and, in severe cases, threaten the life of the host. The anatomical region that is most often affected is the knee (over 50% of cases), involving both the femur and the tibia (see Figure 1). From the clinical point of view there are two treatment options: amputation above the knee, or surgical removal of the tumor (block resection) followed by the reconstruction of the affected site (Malawer and Chou 1995, Simon 1998).

Figure 1. Malignant fibrous knee histiocytoma, INR

There are three therapeutic options essentially (Figure 2) for the treatment of malignant bone tumors of the knee:

- Resection of the tumor and reconstruction by a hinged internal prostheses.
- Amputation of the affected extremity above the knee and the use of a external prosthesis.
- Block resection of the tumor followed by arthrodesis.

a) b) c)

Figure 2. Therapeutic options for the treatment of knee tumors. a) hinge internal prostheses, b) external prosthesis, c) arthrodesis by a spacer and intramedullary nail.

The first option can only be applied when the tumor that affects the knee is not very long in the tibia and may preserve the extensor apparatus. This type of implant presents serious problems of loosening, breaking, rejection, so patients should limit their physical activities to extend the life of the implant (Blunn et al. 2000). The second alternative involves limb amputation above the knee and the use of an external prosthesis. Patients have certain advantages in terms of general function; however they present limitations to walking on steep grades, or slippery or uneven surfaces. Additionally, they suffer skin irritation and phantom limb sensation.

The third option involves the placement of an intramedullary nail into the medullary canal of the tibia and femur, after the resection of the tumor. The nail is complemented by a spacer, which is a metal cylinder whose function is to keep the length of the lower limb, occupying the space that was surgically removed. In addition, the nail is locked by four interlocking pins, two in the femur and two in the tibia. The pins have the function of preventing rotation of the implant and transmitting axial loads.

Arthrodesis by an intramedullary nail has a high stability; however, the complications are nail breaking, neurovascular injury, tibial bone fractures during insertion, no-union and infection (Arroyo et al. 1997). In a clinical trial (Harris et al. 1990) where the three mentioned therapeutic options were evaluated, it was found that patients with knee arthrodesis showed greater stability in the affected limb and showed greater ability to walk on uneven surfaces, or slippery or up and down slopes. These patients could pick objects up from the floor while standing. Patients in this group performed the most demanding activities from the physical point of view. However these patients present limitations on the function of the affected limb. Arthrodesis has the advantage of involving less cost and preserve the patient's anatomy, which is a better option from the emotional point of view. The National Rehabilitation Institute (INR) in Mexico City has its own design of intramedullary nail spacer, as shown in Figure 3, for knee arthrodesis, which has been successfully used in a substantial number of patients (Rico et al. 1996). The implant consists of a solid intramedullary nail of Ti-6Al-4V medical grade alloy, 12 mm diameter and 70 cm length, which has four holes for placement an equal number of blocking pins (3.2 mm diameter), which are inserted through a perforation which is made on both the femur and the tibia cortical and pass through the holes provided for this purpose in the intramedullary nail. The nail is inserted through the femur and tibia medullary canal, which are previously milled. A cylindrical spacer is replaces the knee. This spacer is 20 cm in length and 26 mm in outer diameter. The spacer has the function of allowing bone continuity and of transmitting the load uniformly avoiding the concentration thereof on the pins, particularly on the distal pin. It slides freely on the intramedullary nail, transmitting the load from the femur to the tibia.

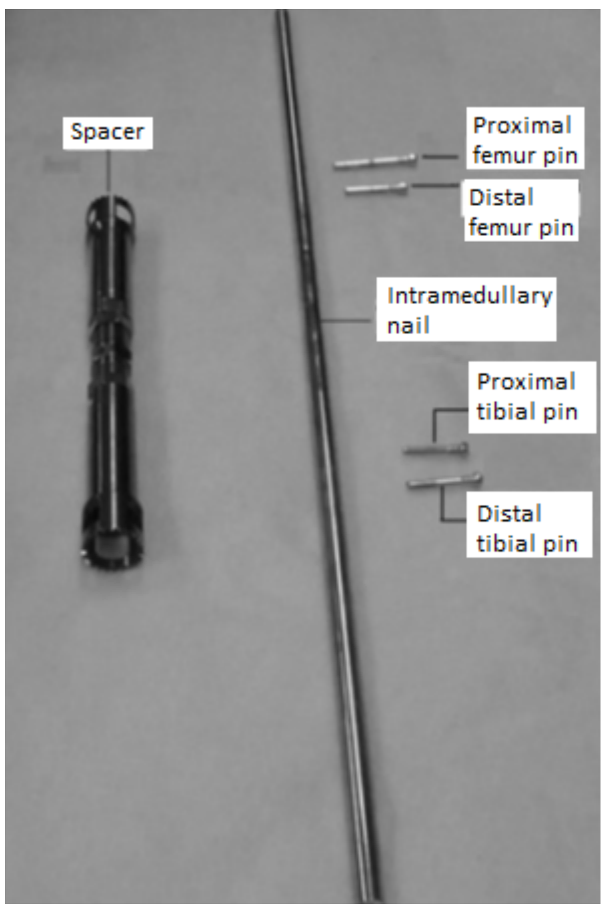


Figure 3. Knee tumor prosthesis, Lab. of Biomechanics INR

During the prosthesis implantation, surgeons perform large resections, so it is necessary to have the support technical of the Laboratory of Biomechanics; this Laboratory has performed research on the impact that design parameters have on the implant's performance when it is subjected to loads.

Although the implant has shown a successful performance, its life is limited by pin loosening, which causes severe pain to patient. This is because the loads on the pins are very high, so the pins plunge into the bone beneath them. In previous studies on this implant (Dominguez et al. 2003), and a similar implant (Dominguez et al. 2004) it has been observed that the location of the pins relative to the location of the resection plays an important role in how the loads are distributed on the implant. The possibility of employing more or less pins has not been explored, neither that of employing pins of different diameter. Similarly, it has been observed that the size of the resection influences the loads occurring on the pins (Araujo et al. 2010).

Furthermore, the Bone Tumor Service at the INR has a Psychology Department which is responsible for providing support to patients with bone tumors; to help them cope with their condition, improve adherence to treatment and to assess their quality of life. Studies on quality of life are a very useful tool for biomechanical research because they provide valuable insight that helps avoid implant failure and reduce complications. This study proposes the application of systemic theories and methodologies such as design of experiments, which allow finding the correlation between the number, diameter and location of the pins for different sizes of resections. The aim is to increase the implant lifespan, making it more reliable and thereby improve the quality of life of the patients. The methodology of Checkland and cybernetic model allow the incorporation of the social aspect to the design of experiments and finally, the transdisciplinary view helps to manage the knowledge of the various areas involved in the diagnosis.

CONTEXT

Environmental Context

The prosthetic system for knee tumors RIMAG, is based mainly at the Bone Tumor Service of the National Rehabilitation Institute (INR) located at the southern part of Mexico City. The INR is one of the National Institutes of Health, which belongs to the Ministry of Health of the Federal Government.

The experimental research takes place primarily at the laboratory of Biomechanics of the INR. The researchers in this laboratory have worked with this implant in the past, so they have relevant information and have the tools (software, machines, sensors, etc.) suitable for its study. For this research, several departments of the INR collaborate. Among these departments are the Bone Tumor Service, Computerized Tomography Service and Quality of Life Department.

To achieve a comprehensive diagnosis of the prosthetic system additional support is given by the Systems Science Engineering team from the School of Mechanical and

Electrical Engineering of the National Polytechnic Institute (Zacatenco Unit), located at the north of Mexico City.

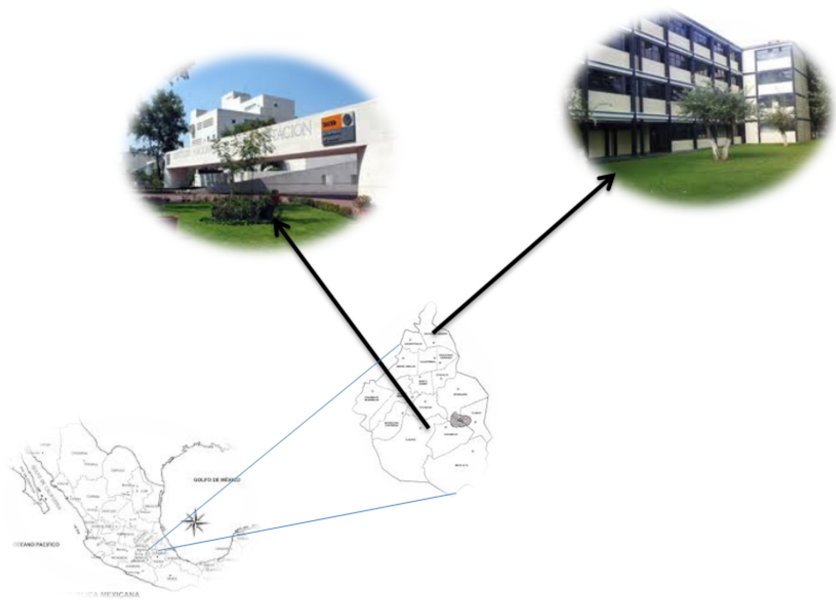


Figure 4. Environmental Context, own creation

Sociocultural Context

The World Health Organization (WHO) and the Panamerican Health Organization (PAHO), report that there are multiple diseases and conditions that cause disability, but in particular diseases and injuries that affect the musculoskeletal system and connective tissue constitute some of the most common causes of disability. These agencies report that there are almost 200 million people in the world, having severe difficulties in their overall functioning, whereas disability affects not only the person suffering, but those who care for them, their family, community and anyone who gives support in the treatment of the disability.

Disability is one of the emerging public health problems, which in recent years has gradually increased; considered as a multidimensional and multifactorial phenomenon.

The National Institute of Statistics, Geography and Informatics of Mexico (INEGI), reported in 2010 that 5.1% of the Mexican population (about 5,739,270 inhabitants) suffered some degree of severe disability, of which 51.1% was composed of women and 48.9% men.

During 2011, the INR treated 11,845 patients with conditions related to the musculoskeletal system that in the short or medium term cause some disability degree (Ibarra et. al. 2013). Out of that total, 312 patients (2.6%) had some type of musculoskeletal system tumor. About this condition, the greatest part of the patients was female with 53.5% (167 patients) and the remaining 46.5% (145 patients) were male. The average age of patients with tumors was 33.48 with a minimum of 2 and a maximum of 86 years. Regarding the occupation of patients in the of Bone Tumor Service, 20.51% (64) were students; 19.55% (61) were housewives; another 19.23% (60) were unemployed; the 15.38% were under 14 years of age and the rest had different occupations like office, dealer or sales, employee, farmer, federal or state employee, retiree or pensioner, etc. In order to determine the socioeconomic status of patients, the Social Service of INR conducted a socio-economic study where the average income per capita was estimated for each of the 6 levels established. Most patients with bone tumors are among socioeconomic levels 2 and 3 (monthly per capita income between 51.04 and 141.53 dollars) with 219 (70.2%).

The problem of tumors has several aspects; one of them is the psychosocial. The diagnosis of a malignant tumor has a devastating effect on the family, because it is a condition that threatens the patient's life and requires major adjustments in the lifestyle of the patient and family. For example, families often have social and financial problems.

In Mexico there is the need to travel to cancer care centers, which results in leaving their family in their communities, and sometimes break up the family, even for a short time.

One consequence of treatment is the social gap in patients, because sometimes they find difficult to return to a useful and active life in society. Following the loss of control in their life, patients may experience changes in personal relationships, as well as a great distress and uncertainty about the future.

According to the INR reports (2000), out of 724 cases of benign bone tumors reported, 110 went to receive treatment after a month of the beginning of symptomatology (Flores 2010). Over 300 cases (almost 50%) did so after a year of the beginning of symptomatology. In the case of malignant bone tumors, out of 363 cases reported, 50 of them went to INR during the first month of the beginning of symptomatology, 110 cases did so after 2 to 3 months and 65 cases after 12 months, as shown in Figure 5.

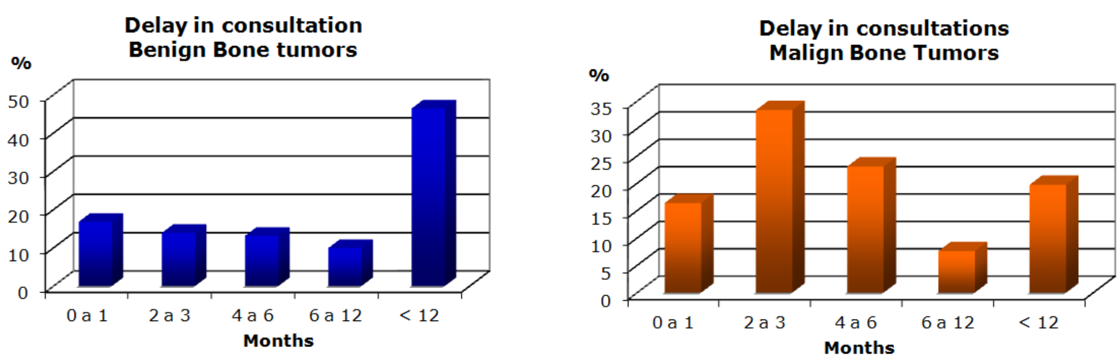


Figure 5. Delay in consultation for patients with benign and malign tumors in the INR, Lab. of Biomechanics INR

Since a high percentage of patients go to health services 2 to 3 months after the symptoms begin, sometimes tumors have extensively covered the soft tissue and articular surface, making it difficult to apply the preservation treatment of the lower limbs.

In case that the patient cannot preserve the joint function, arthrodesis is the procedure that is indicated as salvage surgery after a block resection of a tumor. It has been reported that despite getting a solid arthrodesis, some patients may not be satisfied with the final result because of persistent pain or infection (Flores 2010). The outcome of treatment can limit the function of the joint or limb.

According to (Flores 2010), perceived stress, anxiety and distress of patients increase before the biopsy, probably because they are in the uncertainty of a malignant disease. Moreover, these indicators remained high after the biopsy and even if the diagnosis was good.

The group of patients with bone tumors in Mexico represents a specific population, defined by age and anatomical location of tumor incidence as well as the characteristics of orthopedic-surgical treatments that they are subjected to. For adolescents and young adults, the process of diagnosis and medical treatment may affect the emotional, cognitive and behavioral resources of patients. Patients face situations that affect or impede the continuation of their lifestyle, they are undergoing long-term treatment with side effects that lead to changes in their body image, possible physical limitations and they do not have certainty of a complete or definitive cure.

METHODOLOGY

Cybernetic Model

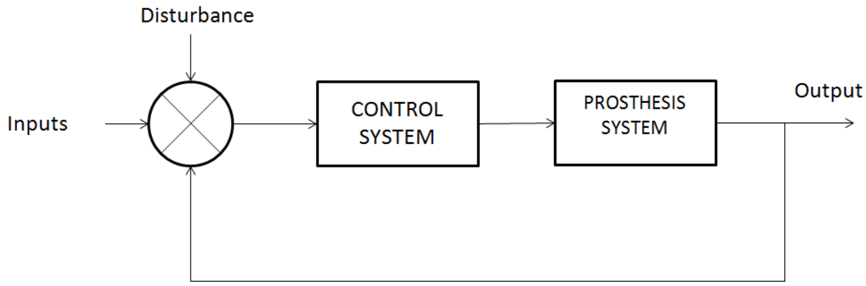
The cybernetic model (Warfield 2006) relates the internal and environmental conditions of a system, and how it changes in response to these relationships. For the prosthetic system, the cybernetic model allows us to understand the whole (prosthesis) and its parts (pins, nail and spacer), the interaction between them and the patient, and the evaluation of the environmental, social and cultural factors about the performance of the prosthesis, in a quick and reliable manner.

Any scientific endeavor involves learning. This process consist of a constant evaluation of the successful activities, learning from mistakes and their possible correction, also is iterative and the feedback of the environment, the researchers and their colleagues is necessary.

Therefore, we propose a feedback cybernetic model because with it is possible to monitor the response of the prosthetic system when a special condition occur such as the wrong usage of the prosthesis by the patient.

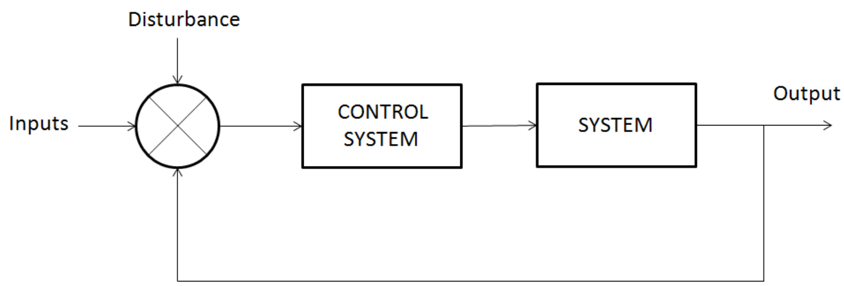
In the case of the tumor prosthesis system, we propose five relevant systems to evaluate: pins-spacer-nail, brain-locomotion, patient's emotions, patient diagnosis, and patient support system.

A simple way to observe the input-output relationships in a feedback system is through the use of block diagrams. Then, it is shown the diagrams of the relevant systems mentioned above.



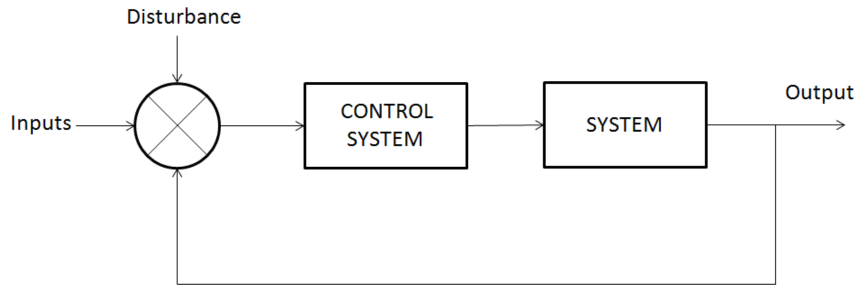
Output: stress measurement at key points.
Control System: experience of biomechanics researchers and surgeons, comparison with other tests.
Inputs: experimental conditions (length and diameter of the nail, position, number and diameter of the pins, quality and size of resection).
Disturbance: the patient does not use correctly the prosthesis.

Figure 6. Pins-spacer-nail feedback diagram, own creation



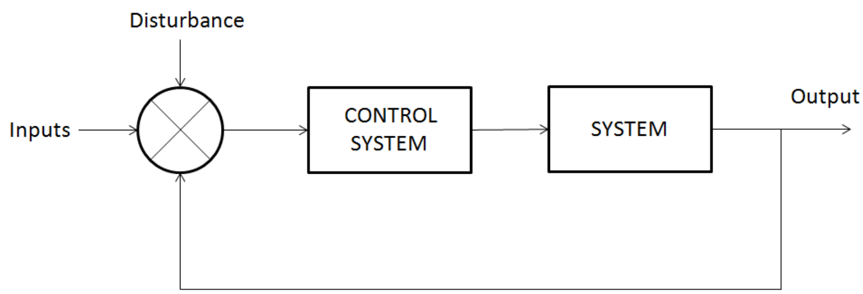
Output: gait performance.
Control System: brain.
System: locomotion of the patient with the prosthesis.
Input: rehabilitation, medication, patient self-recognition.
Disturbance: pain, infection, socio-cultural and economic factors, bad use of the prosthesis.

Figure 7. Brain-locomotion feedback diagram, own creation



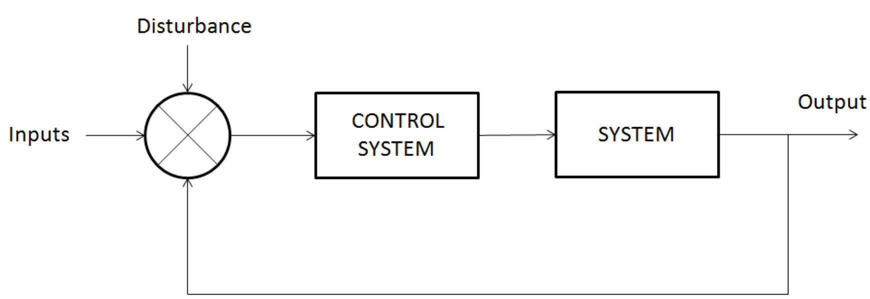
Output: patient's feelings towards their new condition.
System: cognitive and affective skills of the patient.
Control System: Quality of Life Department.
Input: resection of the tumor and reconstruction of the limb.
Disturbance: social segregation, financial problems, break up of the family.

Figure 8. Patient's emotions feedback diagram, own creation



Output: medical diagnosis.
System: patient.
Control System: Medical Institutions.
Input: laboratory tests, Rx, CT scan, physical examination.
Disturbance: use alternative therapies, adherence to treatment by patients.

Figure 9. Patient diagnosis feedback diagram, own creation



Output: labor, financial, social and emotional situation of the patient.
System: family, society, public and private institutions.
Control System: independent agencies,
Input: government support, legislation, social programs.
Disturbance: social segregation, access to public and educational spaces.

Figure 10. Patient support system feedback diagram, own creation

Checkland Methodology

Although the principal goal of this diagnosis is to determine the best configuration of the pins through a design of experiments (hard system), do we should not forget that the patient's quality of life will improve, because the pain will be reduced. One of the most commonly used methodologies to treat problems with high social load, like the assessment of quality of life of a patient with arthrodesis, is the Checkland Methodology (Checkland et. al. 1994).

Below, we show how the Checkland Methodology can be applied in the diagnosis of a prosthetic system.

Phase 1, unstructured problem: is the general observation of the problem. At this stage we recollect all the information provided by the following areas:

Laboratory of Biomechanics: it has been observed that the location of the pins relative to the resection site plays an important role in the distribution of the implant loads; the best location reported is 25 mm of separation between the resection and between each pin (Domínguez et. al. 2003). The resection size influences the loads occurring on the pins. It has been observed (Araujo et. al. 2010) that the load of the femur pins is constant at any change in the resection size; in contrast, the loads on the tibia pins increased at nearly proportional manner with respect to the size of the resection (Figure 11).

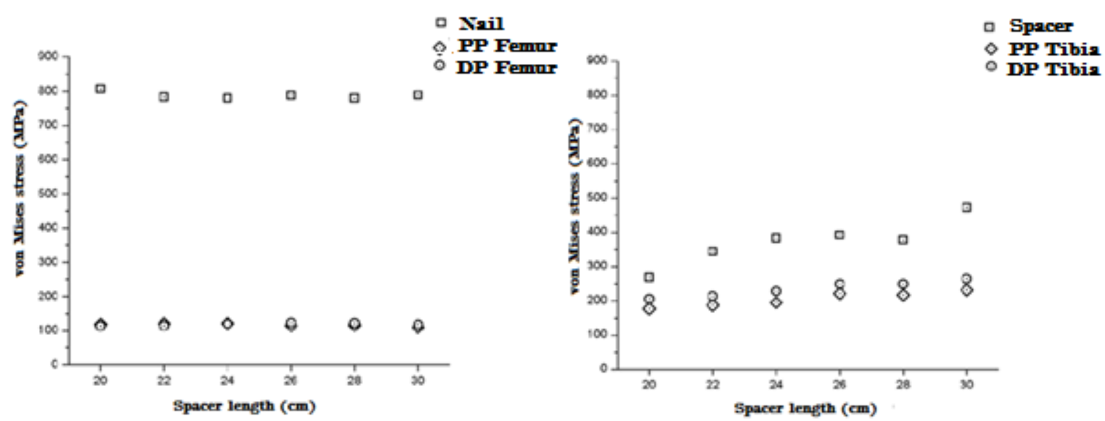


Figure 11. von Mises stress on pins (PP=Proximal Pin, DP=Distal Pin), Lab. of Biomechanics, INR

Bone Tumor Service: During clinical consultation patients report pain or infection. When placing the implant, doctors ask themselves the following research questions: what happens if we place more or less pins?, what is the best place for the pins?, what is the maximum load that the prosthetic system can hold up without causing damage to the patient?

Quality of Life Service: Various tests such as the Beck Anxiety Inventory and Functionality Instrument WOMAC (Western Ontario & McMaster Osteoarthritis Index) were applied to assess the quality of life of 14/37 patients undergoing knee arthrodesis during the years 2003-2007 with a range of 15-80 years. Among the most important results of this monitoring shows that: 70% of patients report mild to moderate pain, some patients present mild to moderate difficulty to perform seven activities of daily life, a score between 0 and 100, the average health status was 60 (40 the lower and the maximum was 100), the number of surgeries performed to these patients are between 1-15 (7 surgeries on average, due to complications). Most patients (42%) had moderate anxiety and depression levels (See Figure 12).

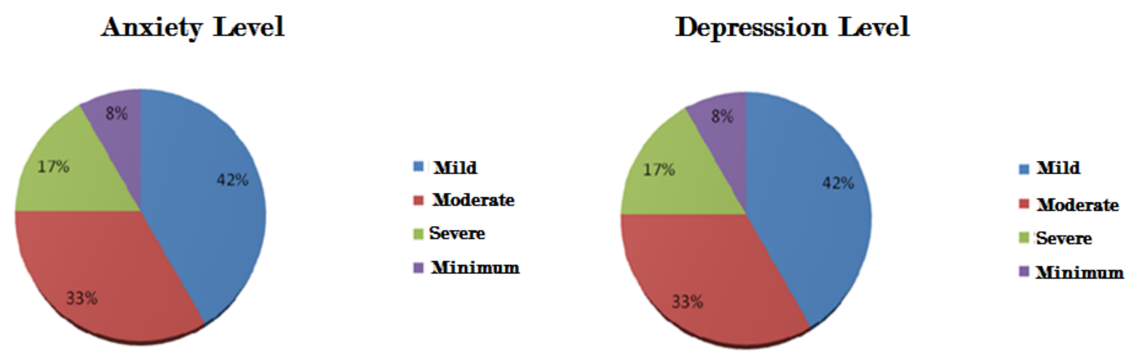


Figure 12. Anxiety and Depression levels in patients with knee arthrodesis in INR, Flores 2010

Phase 2, structured situation: this phase allows classifying the information obtained in the previous phase, and analyzing the solutions proposal by the different areas to find the most viable or combine several solutions through a transdisciplinary view (as shown in Figure 13).

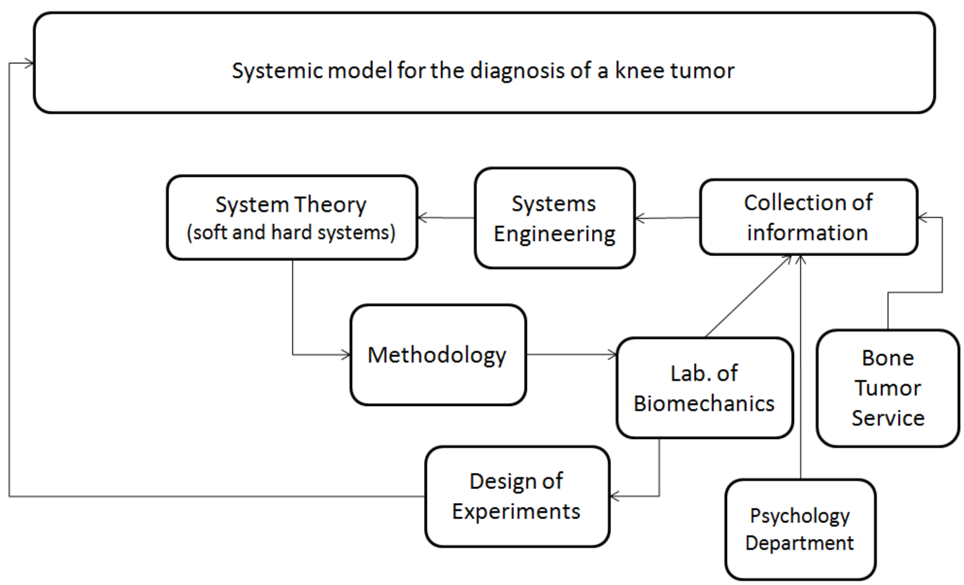


Figure 13. Structured Situation Schema, own creation

Phase 3, definition of relevant systems: from the systems mentioned above we taken as an example the subsystem called pins-spacer-nail in order to produce the root definition through the CATWOE methodology.

Client: patient.
Actor: find the optimal configuration of bolts depending on the size of the resection.
Transformation: perform computational and experimental models for evaluating the performance of the prosthesis.
Weltanschauung: patient's daily life.
Owner: Biomechanics Laboratory.
Environment: National Rehabilitation Institute.
Phase 4, conceptual system: in this phase we could achieve a hybrid methodology with the binding of soft systems (social aspect) and hard systems (design of experiments, it is explained in detail in the next section).

Phase 5, compare conceptual models with reality: at this point the solutions proposed in phase 2 and the results obtained in the preview phase (phase 4) are compared.

Phase 6 and 7, implementation or application: Based on the results of phase 4, prosthetic mechanical redesign system will perform.

Design of Experiments (DOE)

The first step in a DOE (Montgomery 2004) is to identify the response variables of the experiment. In this case, the main goal of the experiment is to minimize the von Mises stresses over the pins, another variable that may also be of interest is to know the maximum value of the average stress in the spacer.

The next step is to define the factors of the experiment. According to previous studies (Dominguez et. al. 2003, Dominguez et. al. 2004 and Araujo et. al. 2010) we suggest to consider the following factors: nail length (70, 75, 80 cm) and nail diameter (10,12, 14 mm), resection size (15, 20, 25 cm), chord length in the crown (2, 4, 6 cm), pin locations (3 locations), number of pins (2 ó 3) and pin diameter (3.6, 3.9, 4.2 mm) and resection quality (good, regular, poor).

Then, according to the nature of the factors involved, the design type is selected. Because the factors have three levels (minimum, medium, maximum) and there are eight factors involved, it is best to use a 3^8 model. This model generates 6,561 different runs, is considered perform a single replication of the experiments, and because of it is not practical to perform this number of runs, we choose to use a fractional model, which allows fewer runs. With the help of Statgraphics Centurion XVI software, the fractionated experiment gets 117 runs.

Transdisciplinary View

To achieve a complete diagnostic of our prosthetic system it is essential that various departments of the health system work together (Figure 14). In this case the transdisciplinary view plays an important role. Transdisciplinary view (Luengo Gonzalez 2012) does not reject the disciplines; it is presented as a new form of communication and knowledge management across different disciplines. The transdisciplinary view may be understood as an approach that transcends the boundaries of individual disciplines to address issues from multiple perspectives, such as the diagnosis of a prosthetic system. The health subsystems proposed for the diagnosis of a prosthetic system are: medical-surgical area, biomechanics experts and the group of quality of life. The medical subsystem provides the knowledge about the pathophysiology of the disease, treatments and surgical aspects of implant. The biomechanical engineering subsystem provides the stress analysis techniques, either experimental or numerical trials. Finally, the quality of life subsystem provides factors related to patient satisfaction, complications and patient self-sufficiency.

The proposed models combine hard and soft methodologies for studying the factor those different design parameters on the performance of the implant, from a systemic point of view, with transdisciplinary perspective.

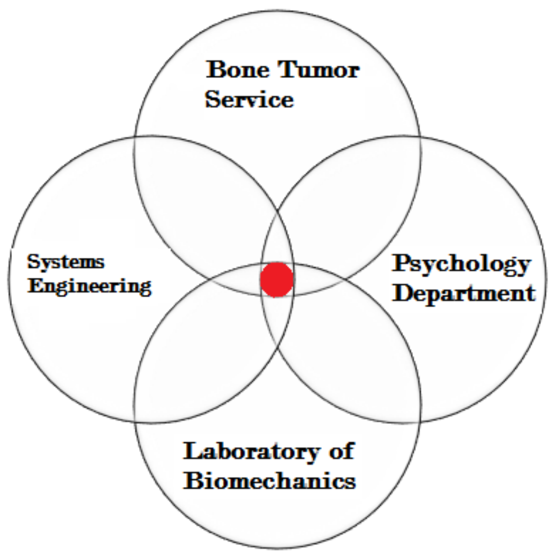


Figure 14. Synergy of the disciplines involved in the diagnosis of a tumor prosthesis, own creation

FUTURE WORK

Once a soft and hard systems methodology has been developed, we will perform the corresponding simulations to the 117 runs for the subsequent statistical analysis of results. As a next step we will perform a mechanical redesign of the prosthesis with the settings that were most significant in previous simulations. As a way to validate the results of these simulations, it is proposed to perform an in vitro model, by mounting the prosthetic system in a synthetic bone and the recreation of the simulated conditions using a load frame and a universal testing machine. Once the redesigned prosthetic system has been placed in patients, their performance will be evaluated by the proposed cybernetic model to consider all aspects involved in the dynamics of the system.

CONCLUSIONS

The goal of this research is to find the optimal configuration of the pins (number, position and diameter) for the best load distribution on the implant and to prevent pins from loosening and sinking into the bone. Although this problem can be solved with a design of experiments (hard system), the researchers in the Laboratory of Biomechanics (INR) have found that in addition to biomechanical factors, there also exist other factors such as socio-cultural, psychological and economic environment surrounding the patient that affect the performance of the prosthesis. Because it is not possible to incorporate these last factors into a design of experiments, the proposal of this paper, which consist of a hybrid methodology (hard systems and soft systems) is presented as the best option for the prosthetic system diagnosis.

It is observed that phases 4 and 5 of the Checkland methodology are the key point for the correct application of the hybrid methodology, because they allow the implementation of simulations and experiments in order to compare the results obtained at these points with the results found in the literature or the hypothesis described by the specialists of the various disciplines involved.

It is important for the hybrid methodology implementation; to first, develop the soft systems methodology, to obtain all possible information about the implant, review the available resources and the medical and engineering fields that will be involved in the process. Based on this information, the right design of experiments will be performed. With the results obtained in the experiments it will be possible to perform a mechanical redesign of the implant, with a better load distribution, and thereby give as a result a better quality of life for patients by decreasing pain and avoiding future surgeries.

The cybernetic model is presented as an important visual resource for the organization of information. It also presents clearly the relationships between the various actors in a complex process, like the prosthesis performance.

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