A TECHNOLOGICAL AND STATISTICAL STATE-OF-THE-ART STUDY REGARDING ACTIVE MOTION-ORIENTED ASSISTIVE DEVICES

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Abstract: Active orthoses and powered exoskeletons, among other denominations, are devices made to attach to one or several human limbs in order to assist or replace its wearer's movement through means of electronically-controlled actuators and/or mechanical brakes. The technology developed for these devices can be used for rehabilitation, general strength enhancement for industrial or military purposes, among other situations. In order to create a comprehensive state-of-the-art work for this class of devices, several online scientific databases were used to gather articles related to this subject. Afterwards, a custom database was created to contain, organize and cross the information gathered from each relevant article. This work presents statistical results regarding the actuation technologies, the man-machine interface sensors and the corresponding interpretation algorithms. There is also a brief study about the localization of the scientific research, according to the targeted body part of the active device. The results show that the DC Motor is, by a wide margin, the most used actuator technology. This margin is reduced when wearable devices with weight constraints are developed. The electromyographic sensors are the most widely used sensors, but when these are grouped into physical variable classes, the force-related sensors show a higher number of occurrences. Regarding the processing algorithms required for the man-machine interface, it is often required to develop a custom algorithm for these devices.

1 INTRODUCTION

Active orthoses and powered exoskeletons, among other denominations, are devices made to attach to one or several human limbs in order to assist its wearer's movement through means of electronically-controlled actuators and/or mechanical brakes. The technology developed for these devices can be used for various purposes, such as rehabilitation (Jia-fan et al., 2010; Yuanjie Fan, 2009), industrial (Yasuhisa Hasegawa, 2010; Low et al., 2005) and general strength enhancement (Kazerooni and Steger, 2006; Cao et al., 2009a).

As seen in Figure 2, from 2005 onwards, the global scientific community has shown a large increase in the overall interest around these devices.

In order to create a comprehensive and organized state-of-the-art bibliographic work, several articles related to active motion-oriented assistive devices, regardless of their purpose, were gathered from seven scientific databases.

There is a lack of a consistent naming convention for these devices, creating some difficulties in the task of gathering scientific bibliography over this subject. Depending on various authors and associated research institutions, several different names have been given to the same kind of devices, regardless of their purpose, technology involved or target body parts. Therefore, in order to gather as much articles related to this subject as possible, the search was repeated for each of the most recurrent terms used to describe these devices.

Afterwards, a database was created to contain, organize and cross the information gathered from each relevant article.

This work presents the statistical results regarding the localization of the scientific research on these devices, the actuation technologies, the man-machine interface sensors and corresponding interpretation algorithms.

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2 STATE-OF-THE-ART DATABASE CONSTRUCTION

In order to gather information into the state-of-the-art database, the following online search engines from scientific research databases were used: ”Science Direct”, ”IEEE Xplore”, ”MetaPress”, ”ACM Digital Library”, ”ASME Digital Library”, ”IOP Science” and ”Emerald”.

For each engine, a search was made for each of the following terms: ”Exoskeleton”, ”Orthosis”, ”Orthesis” and ”Rehabilitation Robot”.

From the search results, all the articles containing a description or a study about an existing active orthosis or powered exoskeleton (regardless of its functionality, purpose or prototype stage) were selected.

The articles retrieved were made available under the ”B-On: University of Porto” program.

This search, conducted during December 2010, resulted in the retrieval of 203 articles. Out of these, 15 were state-of-the-art and/or comparison articles. From each of the remaining 188 articles, various technical and non-technical characteristics were gathered into a custom-made database, using Microsoft Office Access 2010.

The purpose of this database is to provide statistical studies regarding the scientific development of active orthoses and exoskeletons, which can be automatically updated if more articles are added in the future. A simplified representation of the database’s entity-relationship model can be found in Figure 1:

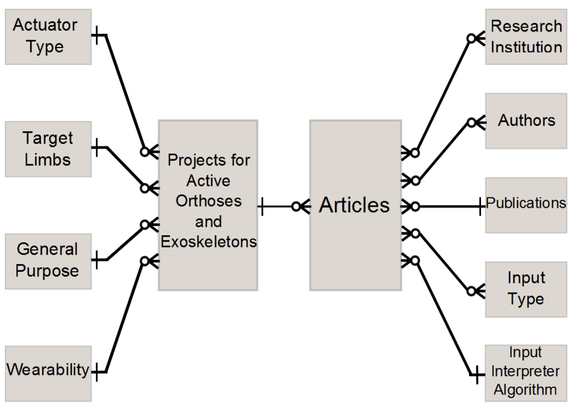

Figure 1: Simplified representation of the database’s entity-relationship model, using Crow’s Foot Notation.

An article is included in the database as part of a ”Project”, which can represent any device from a hardware prototype in development stage to a commercial product.

Each project describes the actuator technology used, the target limbs or body parts, its main and secondary (if available) purpose, its wearability and the related articles.

From each article entry, the database also records its publication, the name of each author and associated research institution, the ”Input Type” (sensors used for the user/patient interface, when applicable) and the ”Input Processing Algorithm” (algorithm that translates the user/patient’s ”will” to move between the sensor interface and the computing system, when applicable).

3 GENERAL STATISTICS

The first general statistics that can be taken from the database is the general commitment from the scientific community regarding active motion-oriented assistive devices. Figure 2 shows the number of articles gathered for each corresponding year of final draft, as well the number of related authors.

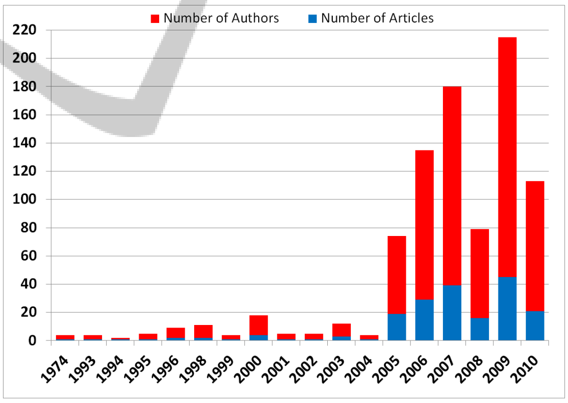

Figure 2: In blue, the number of articles related to active orthoses and exoskeletons gathered per year. In red, the number of authors associated to the gathered articles.

Given that 2005 is the year where a large increase in scientific interest was observed, all the statistical studies presented in the article are, from this point, calculated using articles from the beginning of 2005 onwards.

A relevant information that can be gathered from the database is to determine which are the most dedicated research institutions for this kind of devices, depending on the targeted body part. Figure 3 shows the research institutions with more associated articles for each targeted body part.

The terms ”Lower Limbs” and ”Upper Limbs” are used for devices that attach and actuate over more

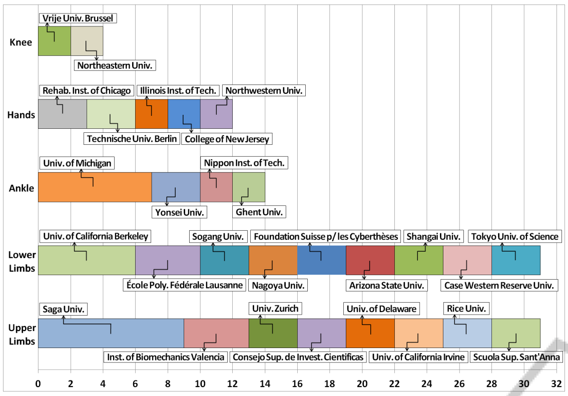

Figure 3: Number of articles associated to Active Orthoses or Powered Exoskeletons, depending on the targeted body part.

than one body part, such as entire limbs. For the "Hands" and "Knee", the graphic considers only research institutions with two or more article associations. For the other represented body parts, the graphic considers research institutions with three or more associations.

Out of the 123 Projects, 89 are primarily dedicated to rehabilitation activities, from retraining motor movements to reestablishing or aiding motor movement to target limbs due to injury or stroke. The remaining 34 Projects are mostly dedicated to strength and/or endurance enhancement, aimed at various activities like agriculture or industrial environments.

4 ACTUATOR TECHNOLOGY

The choice of the Actuator Technology for an active assistive device depends on various factors, such as operation noise and safety, energy efficiency, controllability, among other factors. However, when considering a portable or "wearable" device, where the user must support its weight, the torque/volume and torque/weight become critical factors. The following statistics show the proportions of Actuator Technologies chosen by researchers for active assistive devices depending on their wearability.

Therefore, the results for the "Actuator Type" in each "Project" were crossed with the "Wearability" table (seen in Figure 1) Three types of wearability are considered:

- Not wearable (Figure 4), where the device is fixed to a wall or a table, so the weight is less important (Worsnopp et al., 2007; Banala et al., 2007).
- Wearable while sitting on a wheelchair (Figure 5), where the weight of the device is supported by a wheelchair (Herder, 2005; Rahman et al., 2010).
- Wearable while walking (Figure 6), where the device allows (or is planned to allow, at some point in the prototype stage) the user to walk freely while attached. In this case, the torque-per-weight ratio holds the most importance since the user and/or the device itself have to support the increased weight (Cao et al., 2009b; Sankai, 2006).

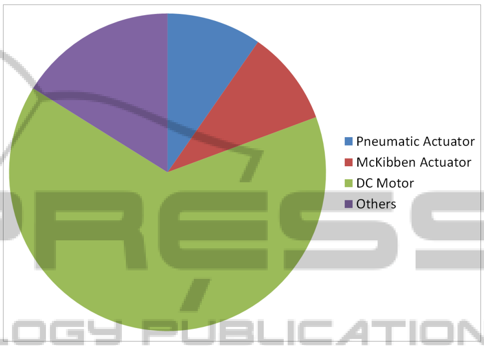

Figure 4: Proportions of non-wearable active orthosis/exoskeleton projects, grouped by actuator technology.

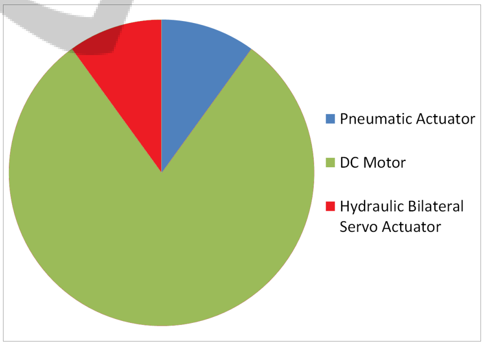

Figure 5: Proportions of active orthosis/exoskeleton projects mounted on a wheelchair, grouped by actuator technology.

The most popular actuator technology used for creating active orthoses and exoskeletons is the DC Motor. This actuator technology, and its various implementations, is one of the oldest actuation technologies used in active devices. Therefore, various and effective control methods are well studied and pre-built motor controllers can be achieved from several manufacturers (Motorcontrol, 2011), making this technology easier to implement from a control standpoint.

However, some newer actuation technologies (i.e. McKibben actuators) have a substantially larger torque-per-weight ratio (Plettenburg, 2005), which

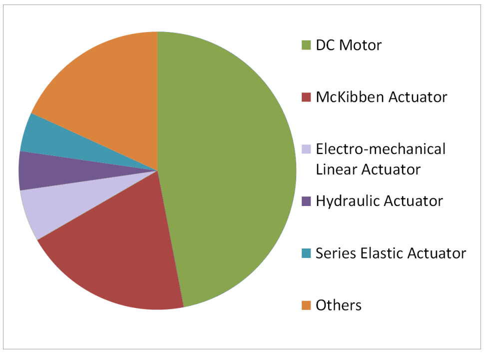

Figure 6: Proportions of wearable active orthosis/exoskeleton projects, grouped by actuator technology.

should provide a practical advantage for weight-dependent, or ”wearable” orthoses and exoskeletons.

The graphic in Figure 6 shows that the weight concerns, when projecting a wearable device, are driving the scientific community to try other actuation technologies with more convenient torque-per-weight ratios, such as McKibben actuators, despite the increased difficulty in developing control algorithms for a stable and safe operation (Daerden, 1999).

5 MAN-MACHINE INTERFACE

5.1 Sensor Technologies

Regarding the following statistics, all the sensor input types that are used for the man-machine interface between the user/patient and the device were gathered. The sensors exclusively used for internal actuator operation generally belong to a different part of the control loop and are more often documented within the scientific studies related to the actuator technology. As these studies may not relate directly to the development of active orthoses and exoskeletons, these sensors weren’t gathered into the database.

This information, represented as ”Input Type” in Figure 1, was taken from each article, as different articles in the same project may refer to different sensor input hardware (Carignan et al., 2005; Carignan et al., 2008).

The sensor technologies were grouped into major categories, with each one determining the type of physical variables each sensor is measuring.

The list of gathered sensor types was divided into the following classes:

- Electromyographic sensors;
- Force-related sensors: consisted of torque sensors, force sensors, floor-reaction-force sensors, force-sensing-resistors and force transducers;
- Angle-related sensors: consisted of potentiometers, rotary encoders, dc motor encoders, goniometers and gyroscopes;
- Other sensors: All the sensor technologies with less than three occurrences like accelerometers, on/off switches, optical tracking devices, among others;
- No Input: referring to devices using automated sequences for rehabilitation/training purposes, without having a direct connection between the user/patient and the device (Costa and Caldwell, 2006; Shibata et al., 2010);
- Undisclosed: term applied in the database when an article doesn’t mention the sensor technology used between the user/patient and the device, which occurs in some articles dedicated to trial tests and their results (Vanderniepen et al., 2008; Boehler et al., 2008).

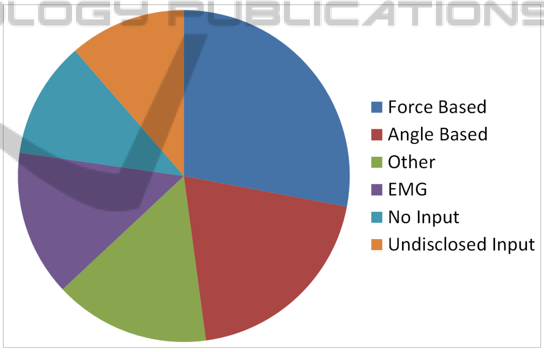

Figure 7: Proportion of sensor technologies, grouped by physical variable classes.

5.2 Input Processing Algorithms

Another technological feature that can be evaluated from the database is the ”Input Processing Algorithm”. This is the algorithm used to process the user’s ”will” to move the actuated limb or body part, using the digital data retrieved from the sensors dedicated to the man-machine interface.

Figure 8 shows the number of occurrences for the most popular algorithms for the man-machine interface used in active assistive devices. Like the sensor technology, different articles belonging to the same project may refer to experimenting different algorithms while using the same orthosis/exoskeleton prototype (Wege and Hommel, 2006; Wege and Zimmermann, 2007). For this reason, this information was taken from each article.

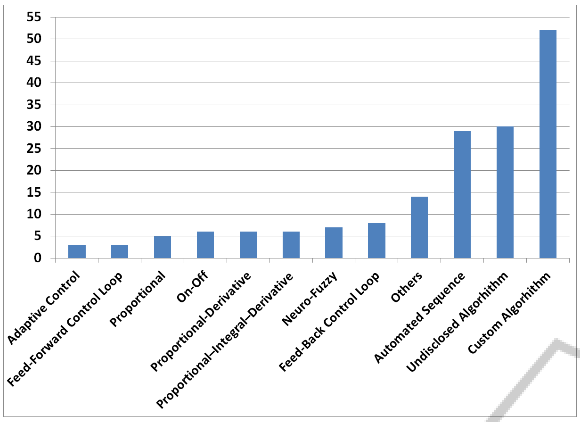

Figure 8: Number of occurrences for Input Processing Algorithms, taken from the gathered articles.

The "Automated Sequence" result refers to the lack of a man-machine interface, and is therefore related to the results for "No Input" in the "Sensor Input" data. Algorithms with less than three occurrences were gathered into a single group called "Other".

"Undisclosed Algorithm" is the term applied when an article doesn't mention what kind of algorithm the device uses for interpreting the man-machine interface(Raparelli et al., 2007).

"Custom Algorithm" refers to either a combination of the other mentioned algorithms or a completely new formula (Andreasen et al., 2005; Kong et al., 2009). In these cases, an "off-the-shelf" solution isn't applied.

6 DISCUSSION AND CONCLUSIONS

As seen in Figure 2, active orthoses and exoskeletons have suffered a recent increased interest throughout the scientific community, starting in 2005. This fact can be explained through general advances in control and actuator technologies, the increasingly larger trend of researching technological solutions for otherwise difficult tasks and the ageing of the population in certain countries.

The actuator statistics show that the most popular actuator for active assistive devices is the DC Motor so far. Although this actuator technology presents a relatively low torque/weight and torque/volume ratio, its matured control methods makes it the most widely adopted choice.

However, when studying a wearable device with weight and volume constraints, as we see in Figure 6, the DC Motor is seen to be adopted in less than half of the studied projects. As actuator technologies with higher torque/weight and torque/volume ratios become mature, it may be expected to see DC Motors being gradually replaced for wearable devices, particularly by McKibben actuators.

Regarding the statistics relative to the sensors used, it can be seen that although force-related sensors are actually being tried out in larger proportions, the magnitude of occurrences is similar for all the classes.

The statistics relative to the Input Processing Algorithm show that most of the time, a custom-made algorithm is necessary to develop an efficient computational method to translate the user/patient's "will" to move the actuated limb or body part. This means that creating an algorithm to efficiently control an active orthosis or exoskeleton usually becomes a very relevant and time-consuming task during the development of a functional device.

As for future work, the Authors' plan is to keep updating the database on a yearly basis, in order to follow the technological advances and trends on active motion-oriented assistive devices.

REFERENCES

Andreasen, D. S., Allen, S. K., and Backus, D. A. (2005). Exoskeleton with emg based active assistance for rehabilitation. In *IEEE International Conference on Rehabilitation Robotics*.

Banala, S. K., Kulpe, A., and Agrawal, S. K. (2007). A powered leg orthosis for gait rehabilitation of motor-impaired patients (alex). In *IEEE International Conference on Robotics and Automation*.

Boehler, A. W., Hollander, K. W., Sugar, T. G., and Shin, D. (2008). Design, implementation and test results of a robust control method for a powered ankle foot orthosis (afo). In *IEEE International Conference on Robotics and Automation*.

Cao, H., Ling, Z., Zhu, J., Wang, Y., and Wang, W. (2009a). Design frame of a leg exoskeleton for load-carrying augmentation. In *EEE International Conference on Robotics and Biomimetics*.

Cao, H., Ling, Z., Zhu, J., Wang, Y., and Wang, W. (2009b). sign frame of a leg exoskeleton for load-carrying augmentation. In *IEEE International Conference on Robotics and Biomimetics*.

Carignan, C., Liszka, M., and Roderick, S. N. (2005). Design of an arm exoskeleton with scapula motion for shoulder rehabilitation. In *International Conference on Advanced Robotics*.

Carignan, C., Naylor, M. P., and Roderick, S. N. (2008). Controlling shoulder impedance in a rehabilitation arm exoskeleton. In *IEEE International Conference on Robotics and Automation*.

Costa, N. and Caldwell, D. G. (2006). Control of a biomimetic "soft-actuated" 10dof lower body exoskeleton. In *International Conference on Biomedical Robotics and Biomechatronics (BioRob)*.

Daerden, F. (1999). *Conception and Realization of Pleated Pneumatic Artificial Muscles and their Use as Compliant Actuation Elements*. PhD thesis, Vrije Universiteit Brussel.

Herder, J. L. (2005). Development of a statically balanced arm support: Armon. In *IEEE International Conference on Rehabilitation Robotics*.

Jia-fan, Z., Yi-ming, D., Can-jun, Y., Yu, G., Ying, C., and Yin, Y. (2010). 5-link model based gait trajectory adaption control strategies of the gait rehabilitation exoskeleton for post-stroke patients. *Mechatronics*, 20, Issue 3.

Kazerooni, H. and Steger, R. (2006). The berkeley lower extremity exoskeleton. *Transactions of the ASME*, 128.

Kong, K., Moon, H., Hwang, B., Jeon, D., and Tomizuka, M. (2009). Impedance compensation of subar for back-drivable force-mode actuation. *IEEE Transactions on Robotics*, 25:Issue 3.

Low, K. H., Liu, X., and Yu, H. (2005). Development of ntu wearable exoskeleton system for assistive technologies. In *International Conference on Mechatronics and Automation*.

Motorcontrol (2011). List of companies providing dc motor drives - www.motorcontrol.com/2007homepagelinks/dccompanies.htm.

Plettenburg, D. H. (2005). Pneumatic actuators, a comparison of energy-to-mass ratios. In *Proceedings of the 2005 IEEE 9th International Conference on Rehabilitation Robotics*.

Rahman, M. H., Saad, M., e, J. P. K., and Archambault, P. S. (2010). Exoskeleton robot for rehabilitation of elbow and forearm movements. In *Mediterranean Conference on Control & Automation, Volume 18*.

Raparelli, T., Zobel, P. B., Durante, F., Antonelli, M., Raimondi, P., and Costanzo, G. (2007). First clinical investigation on a pneumatic lumbar unloading orthosis. In *International Conference on Complex Medical Engineering IEEE/ICME*.

Sankai, Y. (2006). Leading edge of cybernics: Robot suit hal. In *SICE-ICASE International Joint Conference*.

Shibata, Y., Imai, S., Nobutomo, T., Miyoshi, T., and ichiroh Yamamoto, S. (2010). Development of body weight support gait training system using antagonistic bi-articular muscle model. In *Annual International Conference of the IEEE EMBS, Volume 32*.

Vanderniepen, I., Ham, R. V., Damme, M. V., and Lefeber, D. (2008). Design of a powered elbow orthosis for orthopaedic rehabilitation using compliant actuation. In *International Conference on Biomedical Robotics and Biomechatronics (BioRob)*.

Wege, A. and Hommel, G. (2006). Development and control of a hand exoskeleton for rehabilitation of hand injuries. In *Human Interaction with Machines*.

Wege, A. and Zimmermann, A. (2007). Electromyography sensor based control for a hand exoskeleton. In *Electromyography Sensor Based Control for a Hand Exoskeleton.*

Worsnopp, T. T., Peshkin, M. . A., Colgate, J. E., and Kamper, D. G. (2007). An actuated finger exoskeleton for hand rehabilitation following stroke. In *IEEE International Conference on Rehabilitation Robotics*.

Yasuhisa Hasegawa, Kosuke Watanabe, Y. S. (2010). Performance evaluations of hand and forearm support system. In *Conference on Intelligent Robots and Systems, IEEE/RSJ International*.

Yuanjie Fan, Y. Y. (2009). Mechanism design and motion control of a parallel ankle joint for rehabilitation robotic exoskeleton. In *IEEE International Conference on Robotics and Biomimetics*.