Quantitative motor function evaluation: the VAMA project experience

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Abstract

This paper aims at reviewing the experience maturated over the past decade by this group in the framework of the VAMA (Italian acronym for "evaluation of motor ability in the elderly") project. The objective of that research programme was to devise quantitative methods for assessing the locomotor functional limitation of a given individual and, as a further step, for investigating the relationship between relevant impairments and disability. This was accomplished through the biomechanical analysis of a battery of selected motor tasks as executed by groups of elderly individuals. The attainment of this objective entailed the following methodological steps: increasing the resolution with which the human movement is observed; enhancing the information contained in movement-related data by applying models of the musculoskeletal system; extracting the relevant information by using specific methods of knowledge discovery from databases.

Keywords: biomechanics, movement analysis, musculoskeletal modelling, data mining, motor ability assessment

Introduction

The objective of this paper is to review the experience acquired over the past decade by this group in the framework of the VAMA (Italian acronym for "evaluation of motor ability in the elderly") project. The objective of the research programme was to devise quantitative methods for assessing the locomotor functional limitation of a given individual and, as a further step, for investigating the relationship between relevant impairments and disability.

According to the ICF, the International Classification of Functioning, Disability and Health [1], '*disability is the umbrella term that includes impairment, activity limitation, and participation restriction*'. These three components of disability are described from the following perspectives: body systems or anatomical parts, individual, and societal. It is evident that bioengineering, in general, and biomechanics, in particular, may successfully deal with the former two components.

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In the framework of the VAMA project, a multidisciplinary approach was proposed that required the collaboration of geriatrists, physiologists, movement analysts, and computer scientists. Special emphasis was given to the objective of evaluating motor ability in the elderly.

Evaluation of motor ability: the clinical approach

In the clinical practice, mobility limitation assessment (MLA) tests are implemented to assess the mobility limitations of an individual and are part of the clinical examination pathway. Based on this examination, a treatment is chosen and applied so as to enhance the mobility of the individual. MLA tests may be based on structured interviews, questionnaires, collection of anamnestic data, and/or observation (qualitative and/or quantitative) of the individual during the execution of a certain motor task. Depending on which of these methods is used, MLA tests can be distinguished in three categories: qualitative, semi-quantitative, and quantitative tests.

Qualitative MLA tests are mainly based on questionnaires. A wide variety of standard scales for scoring self-reported information concerning impairment or mobility limitation has been developed. In particular, qualitative MLA is often based on self-reported difficulty or need for help in the execution of basic self-care tasks (ADL, like eating or dressing) or more complex activities (Instrumented ADL, like shopping or cooking).

Semi-quantitative MLA tests use the direct observation of a patient while performing one or more motor tasks [2,3]. The motor tasks taken into consideration are generally related to ADLs. Specifically, the operator controlling such MLA tests, typically a physical therapist or a medical doctor, scores the quality of the execution of each of the tasks taken into consideration in the test, according to a predefined scale. The semi-quantitative tests allow for a higher level of objectivity with respect to the qualitative tests, since they can only be administered by competent persons. However, such evaluation remains subjective.

Quantitative MLA tests use basic measurements, such as the time needed to execute a certain activity, or distances associated with the execution of standardised motor tasks [4,5]. These tests have been devised with the aim of overcoming the lack of accuracy and repeatability exhibited by the qualitative or semi-quantitative tests illustrated above. In particular, with respect to the latter, quantitative tests exhibit greater sensitivity to the variation of the individual's functional status.

In the context of the VAMA project, among conventional clinical MLA tests, a battery was devised for an overall description of the target populations. Four domains were investigated: clinical and functional history, physical examination, pathological conditions, and functional status. Subject history and his/her physical examination and assessment of comorbid conditions (Cumulative Illness Rating Scale [6]) pertained to the first three domains, while tests as Functional Independent Measure [7], Geriatric Depression Scale [8], Mini Mental State Examination [9], Nottingham Extended Activities of Daily Living Index [10], Short Physical Performance Battery [5], and Performance Oriented Mobility Assessment [2] (both balance and gait subsets) were included in the fourth domain.

Such MLA tests are generally not very time-consuming, inexpensive, and well-accepted by the test subjects. On the other hand, however, they have poor sensitivity, cannot detect borderline conditions, and supply insufficient information for the identification of the causes of movement alterations and/or for the evaluation of their type or severity. Furthermore, the motor strategy adopted by the subject during the execution of a properly selected motor task cannot be assessed by mobility tests alone, due to lack of relevant quantitative information.

Evaluation of motor ability: the contribution of instrumented movement analysis

Quantitative MLA is an intriguing objective of clinical biomechanics. Of course, the necessary pre-requisite for this objective to be pursuable is that mobility limitations ultimately express themselves as measurable alterations of the movement mechanics. In this case, the biomechanical approach supplies thorough, objective, and reliable information.

Instrumented movement analysis aims at determining quantities, either measured or estimated using mathematical models of the musculoskeletal system, that describe movement and the relevant causes. Normally, the measured quantities are: skin point kinematics, external forces, anthropometric quantities, electrical activity of muscles, gas exchange. The estimated quantities are: kinematics of internal anatomical landmarks and of both segment and whole body centres of mass, relative movement between adjacent bones (joint kinematics), forces (or moments) exerted by muscles and tendons, ligaments and bones, muscular mechanical work/power and system energy variation, and metabolic energy. However, movement analysis laboratories exhibit some limits. Accuracy and precision of results, cost (purchase of equipment, time involved in experiments, data processing), and plethora of information provided (high number of variables and/or parameters) are some of the relevant problems. These,

of course, have a different impact whether the objective is research or an application, such as in a clinical decision making process.

In order to achieve a MLA, quantitative information mostly related with muscular strength and balance control is needed. In the context of biomechanical analysis, this information is sought by the quantitative investigation of suitable motor tasks, selected according to ADL-related criteria. In particular, movements most frequently referred to are level walking [11,12,13] and upright posture maintenance [14,15].

Currently, for assessing functional status, biomechanics provides the typical tools of a movement analysis laboratory. These tools allow for overcoming the problems related to evaluation subjectivity typical of the MLA approach. In this way, the following quantitative descriptions can be obtained: function of body systems and the relevant changes (assessment of impairment); strategies adopted by an individual executing a selected motor activity; difficulties encountered in doing that activity (assessment of activity limitation).

Measured experimental data are processed using analytical models of the musculoskeletal system exhibiting varying degrees of complexity depending on the objective. In particular, the analysis of a motor task carried out using such biomechanical approach can provide thorough and detailed information concerning joint kinematics, muscular forces at joint level, segmental and whole body energy variations, and the work that muscular forces make in order to realise these energy variations. According to the "classical" approaches used in biomechanics, this information is generally obtained performing either inverse dynamics calculations or forward dynamics modelling.

It is important to highlight that both skeletal kinematic and kinetic data obtained during movement are prone to errors that may hinder the underlying information. Despite the technological progress that has characterized measurement instruments in the course of the last decades, the state of the art of knowledge in movement analysis indicates that the improvement of the accuracy with which relevant quantities can be estimated is a critical challenge for the future [16]. Our group is committed with this issue and improved algorithms were devised to reduce errors and artifacts that affect movement measurements and relevant estimates [17,18].

Evaluation of motor ability: the Minimum Measured Input Models

Although biomechanical analysis may surely represent a tool to build up clinical knowledge, such knowledge needs to be further defined, understood and organised, and an interdisciplinary effort is required to translate the biomechanical techniques into clinical protocols. Based on the above considerations, the number of variables measured within the biomechanical test should be reduced. Since experimental data do not necessarily lend themselves to straightforward interpretation in terms of mobility, these data should be fed as input to a model of the neuro-musculoskeletal system or of a portion of it, able to output information more directly interpretable in mobility terms. To this aim, such a model should already incorporate all the information known a-priori about the subject and the motor task. This implies that the complexity of the biomechanical experimental apparatus would be transferred, to the maximal feasible extent, to the model used to process the experimental data. This type of models allows minimising the number of measured variables needed for the assessment of the functional status of an individual, i.e. the number of variables the model itself receives as input. For this reason, these models have been named Minimum Measured Input Models, MMIMs [19].

In order to achieve typical clinical objectives, such as motor functional assessment pursued at a global (person) or local (joint or district) level, two MMIMs were developed, which received as input only measurements taken by dynamometers, i.e. the resultant force and moment representing the interaction of the subject with the environment, together with a few, easy to acquire, anthropometric and geometric parameters.

The first MMIM draws inspiration from a very essential way of describing human motor acts. This is based on a Telescopic Inverted Pendulum (TIP) representation of the musculo-skeletal portion involved in movement during the execution of a certain motor task [20]. The TIP model receives as input relevant centre of mass trajectory, mass, and constraint location, and gives as output the kinematics and kinetics of three actuators that are supposed to move the link and that are interpreted as muscle-equivalent effectors. This model takes into consideration only the kinematics of the centre of mass and the dynamic actions on it. As such, the model allows for the assessment of motor functional status at a global level. In order to allow for functional assessment also at subsystem level, and particularly at joint level, a second MMIM was developed. This model, named JAGO (Joint Angle Generation using Optimisation), is based on a multi-segmental representation of the musculo-skeletal system [21]. The JAGO model, as the TIP model, receives as input the measured external forces, the initial and final posture geometry and a few anthropometric measurements, and estimates joint kinematics by applying a constrained optimisation algorithm. This algorithm minimises, through an iterative process, a cost function based upon a maximal similarity criterion between the measured external forces and the external forces estimated, at each iteration, by solving an inverse dynamics problem.

The two MMIMs presented above have been validated in relation to their capability of discriminating different motor strategies. To this purpose, they have been applied for the analysis of the Sit-to-Stand (STS) motor task [22] aiming at highlighting the different motor strategies adopted by elderly people with respect to young people. In the context of the VAMA project, MIMMs were also successfully applied in a clinical context. In particular, it was shown to enhance mobility assessment of chronic stroke patients with different motor ability levels and allow for subject-specific motor strategy identification [23].

Evaluation of motor ability: the contribution of computer science

In the VAMA framework, the administration of the different MLA tests was managed and the relevant items acquired by using an interface purposely developed which allowed to store data directly in a Microsoft Access database [24]. The system was designed to work in a multi-centre context, allowing the collection of a great quantity of data in a single data repository.

The combination of MLA test with instrumented movement analysis provides plethoric information that, normally, the clinician finds difficult to handle. Computer graphics and artificial intelligence tools may help in this respect, but are not usually at hand to the normal user. While comparing biomechanical tests with clinical questionnaires, with the goal of evaluating their relevant efficacy in describing a specific motor task and of supporting the use of objective quantitative assessment tools, only few parameters are typically analysed using basic statistical approaches [25]. The selection and correct use of tools for the extraction, management, and interpretation of such an amount of data may determine the success of the analysis.

Data mining (DM) has been shown to be successful in extracting information from medical data. Relevant methodologies integrate different techniques to discover new knowledge by searching for hidden rules and patterns [26,27]. As opposed to classical data interpretation, which relies on human a-priori knowledge and experience and therefore is exposed to biased results and to missed valuable information [28], DM is able to provide a more complete and unbiased picture of the phenomenon under investigation.

In the context of the VAMA project, a Search for Association Rules was applied. This technique aims at finding rules among items of a database [29], which are expressed by means of logical implications associated with a percentage of occurrence (confidence of the rule). The algorithm does not require hypotheses regarding the data nor a-priori knowledge. The algorithm, originally designed to deal with qualitative variables, was modified so that quantitative biomechanical features could also be analysed [30]. This technique has a great potential in biomedical applications, particularly in discovering knowledge regarding disease diagnosis and prediction [31] and showed to be appropriate, if applied to parameters included in experimental databases [32]. Association mining is particularly well suited when informative variable pairs are sought among unrestricted set of attributes. The application of the mentioned DM technique aimed at: a) increasing the knowledge about the mechanics of a motor task; b) globally evaluating functional limitation in the elderly; c) discovering previously hidden relationships between biomechanical and clinical items.

The VAMA database, as used in different research studies, contained more than 85,000 recorded values, obtained from different measures pertaining to a group of 130 medically stable elderly volunteers (age 75 ± 6 y.o.). Relevant measures included the administration of the different MLA tests and, also, data obtained from a set of variables extracted using a TIP model from STS test repetitions performed immediately after. The STS dataset included 36 labelled biomechanical features (maximum values and relevant time of occurrence). DM was performed on the STS dataset [30] and on the different datasets obtained by joining different pairs of clinical tests [33] or the STS dataset to each clinical dataset at a time [34]. The definitions between the items of the investigated database represented the knowledge regarding relationships between clinical and STS items, previously hidden.

A large set of rules was found and typical patterns drew for the STS motor task. The type of information extracted may help in drawing typical patterns and relationships valid for normal elderly persons. The extracted knowledge was also referred to obvious relationships such as those related to symmetry between right and left coordinates or to those referred to motor task time ratios. For each STS feature, the lowest and highest values of the most populated item delimited a range that can be interpreted as characteristic of both the analysed population and the executed task. For instance, the group included in the database executed the STS test exerting low power values. Small values of couples and velocities suggest typical strategies of energy minimisation in executing the motor task. Moreover, some STS items were confirmed as typical of the specific movement executed. The contemporary presence of STS features and clinical parameters among the resulting definitions can be attributed to the relationship between the STS and the specific clinical test. Each clinical test showed a different degree of connection with the biomechanical test. MLA tests including the execution of locomotor tasks [2,5] confirmed the expected strong connection with the biomechanical test.

The DM analysis showed that some of the results obtained with the clinical tests were confirmed by the STS test. This outcome increased significantly the clinical applicability of the biomechanical test and gave meaningful

hints about information redundancy and about the design of an optimised battery of MLA tests. Since the biomechanical test is quantitative and, therefore, objective and reliable, its integration in the clinical context may significantly improve the quality of the information obtained. Whereas associations, and then redundancy, are pointed out, it would be plausible to administer only the biomechanical test. The application of DM to the VAMA database showed that clinical and biomechanical data originating from different contexts can be fruitfully combined to increase the level of knowledge regarding motor ability of a specific group of subjects. The information extracted about elderly subjects allows to highlight typical rules that may serve as a knowledge-based tool for the detection of possible deviation from the normality when a new elderly subject is evaluated.

Conclusions

The research work carried out by the authors in the framework of mobility evaluation, briefly summarised in these pages, maturated in an environment characterised by a marked multidisciplinarity.

From both the methodological and clinical point of view, further steps are in progress together with the latest technological advancements. Imaging techniques are more easily accessible and may be used to obtain more accurate measurements and a more repeatable kinematics [35,36] that may favour the design of new generation movement analysis protocols that may eventually flow into the clinical practice. This is the era of wearable technologies that support the conception of new MMIMs, based on the output of these systems and applied to intriguing problems, such as those requiring the investigation of the mechanics of the upper body during walking [37]. Finally, the experience of using Data Mining need to be consolidated, not only for describing individual mobility but, even more, for predicting the effects of an intervention or of a physical training on the individual mobility for elderly [38] or for disabled people.

All the mentioned advancements are expected to give a significant contribution in the context of performance assessment of living subjects in their own living context and not only for the assessment of capacity in standard laboratory environment.

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