DEVELOPMENT OF SOFTWARE FOR COMPREHENSIVE ANALYSES OF FORCE PLATE MEASUREMENTS: TECHNICAL NOTE

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Abstract:

This technical note summarizes the development of a software solution aimed at data acquisition and analyses and results reporting on the tests performed on a force plate. In the introduction, the history of force plate development is reviewed, followed by a description of the process of ground reaction force measurement data acquisition and parameterization. The second part is a short description of five groups of the force plate based tests used to evaluate human movement: (i) static balance, (ii) dynamic balance, (iii) locomotion and body transfer, (iv) fast alternating movements, and (v) strength and power tests. This is followed by the main part in which we present a technical solution, describe the software's conceptual structure by test modules, point out the most important functions and graphically present a concise overview of the tests that the software is designed to handle. We conclude with ideas for further development and future directions.

Key words: *biomechanics, assessment, instrumentation, reporting*

Introduction

When uni- or bi-pedal postural or locomotion activities are being performed, the body is acting on the ground under the feet with a dynamic force (i.e. action force) and the ground is reacting on the body with an identical force in the opposite direction (i.e. ground reaction force (GRF) (Winter, 2004). GRF, as the most common force acting on the human body, can be either calculated from kinematical and anthropometrical data or measured directly using a force plate (FP) (Wong, Wong, & Lo, 2007). The first FP was designed and built by a French scientist Étienne-Jules Marey at the end of the 19th century (Novacheck, 1997).

Many types of force sensors (strain gauge, capacitance gauge, piezo electric, piezo resistive, etc.) have been developed over the years and thereafter the availability of these devices on the market has enabled mass production of force plates with sensors embedded in stiff mechanical frameworks (for a review see Lee & Nicholls, 1999). These have become one of the most commonly used measurement tools in biomechanics. Today, there are several FPs on the market with different characteristics (e.g. size, capacity, precision, sensor technology, price, etc.), depending on their intended use (Nardone & Schieppati, 2010).

FP is only a part of a GRF measurement system. The signals generated in the sensors must be amplified and analogue-to-digital converted in order to be ready for acquisition by a computer. This hardware is normally what is offered by the manufacturers on the market. However, for a GRF measurement system to become fully operational and for the user to get the most out of it, computer software is needed. The latter is often a weak point of commercial products, since existing software solutions often have at least one of the following deficiencies: (i) a specialization on a certain group of tests only; (ii) the absence of a thorough parameterization of the GRF signals; (iii) the use of quantification indexes which are not explicitly explained and that possess unknown metric characteristics; and (iv) a dedication to a single FP manufacturer. The latter specifically relates to the fact that the manufacturers offer software that can only be used with their FPs, thus protecting companies' intellectual property.

Many recent advanced scientific developments of routines, tests and new ways of parameterization of FP measurements have not been brought into regular research and professional practice yet. Furthermore, several laboratories do not have their own engineering support which can be an important limitation for conducting some studies. Therefore, the aim of our technical developmental project was to integrate the existing knowledge in the field of human movement science and to develop an open Measurement, Analysis and Reporting Software (MARS) for use with different FP types.

From science to practice

The development process began with a thorough review of the existing scientific literature and available MARS-like software products on the market. From what we learned from this review, we were able to classify the tests for which an FP has been used for the evaluation of human movement into one of five groups of tests: (i) static balance, (ii) dynamic balance, (iii) locomotion and body transfer, (iv) fast alternating movements, and (v) strength and power. A brief review of the existing commercial FP software testing functions is presented in Table 1.

Static balance is the ability of a human body to maintain a specific posture as still as possible. Most commonly the so-called quiet stance tests are used for its assessment. Because of the dynamic characteristics of the neuromuscular system and the inherently unstable mechanics of the human posture, the human body sways continuously. The specific characteristics of this sway are influenced by several factors such as the size of the support area (Pan, Chiou, Kau, Bhattacharya, & Ammons, 2009), the height of the body's centre of gravity (Rosker, Markovic, & Sarabon, 2011), age (Abrahamova & Hlavacka, 2008), injury (Lysholm, Ledin, Odkvist, & Good, 1998), footwear (Sarabon, Rosker, Loefler, & Kern, 2010), mental attention (Schaefer, Krampe, Lindenberger, & Baltes, 2008), sensory restriction (Kuo, Wang, & Hong, 2010), etc. FP is a commonly used tool for the acquisition of the body sway data which in this case is expressed as the movement of the centre of foot pressure (COP) over time. During the long history of the body sway research, multiple ways of COP analysis and parameterization have been developed. These techniques encompass the following types of analysis: (i) global or standard analysis (Baratto, Morasso, Re, & Spada, 2002), (ii) diffusion plots (Chiari, Cappello, Lenzi, & Della Croce, 2000), (iii) density plots (Jacono, Casadio, Morasso, & Sanguineti, 2004), (iv) recurrence quantification, (v) sample entropy (Borg & Laxaback, 2010; Richman & Moorman, 2000), and (vi) rambling/trembling (Zatsiorsky & Duarte, 1999, 2000). The calculated parameters can be either planar/general or direction-specific.

In addition to sustaining static postures, everyday functional situations often require ***dynamic***

Table 1. Overview of some commercial FP software

Product / module	**CMJ**	**SJ**	**DJ**	**RCMJ**	**RH**	**LJ**	**SQ**	**FL**	**SS**	**SA**	**TU**	**LOS**	**BS**	**FM**
Arsalis*														X
All Sport Systems*													X	
MoveTest*									X	X			X	
Biometrics									X				X	
AMTI AccuPower	X	X	X	X	X	X								
AMTI Balance Clinic													X	
AMTI Balance Trainer												X		
AMTI Bioanalysis										X		X	X	X
Bertec BalanceCheck Screener												X	X	
Bertec BalanceCheck Trainer												X	X	
Leonardo Mechanography RES	X	X	X	X	X				X				X	
Kistler Bioware													X	X
Neurocom							X	X	X	X	X	X		
Simi*	X	X	X										X	
Hytek*													X	
Pro-Vec Plus*										X		X	X	
BTS bioengineering*										X			X	
HUR labs*	X	X	X										X	

Legend: CMJ = countermovement jump; SJ = squat jump; DJ = drop jump; RCMJ = repetitive countermovement jumps; RH = repetitive hopping; LJ = long jump; SQ = squat; FL = forward lunge; SS= sit-to-stand; SA = step analysis; TU = turn; LOS = limits of stability; BS = body sway; FM = free measurement.

(Note: * - information gathered from the publically available internet sources).

balance control. It needs to be stressed here that dynamic balance is a component of several other movement activities (e.g. walking, sit-to-stand movements, stair climbing, landing, stopping, etc.) (Bardy, Oullier, Bootsma, & Stoffregen, 2002), but for the purpose of sub-grouping FP tests we intentionally divided these tests on the basis of their predominant characteristics. Many clinical and laboratory tests for dynamic balance assessment have been developed with the aim of improving repeatability and sensitivity of the evaluation (Yelnik & Bonan, 2008). In this respect, laboratory tests with many conceptually different approaches have been reported (for a review see Panjan & Sarabon, 2010). However, tasks in which a subject is voluntarily shifting the centre of body mass (i.e. COP displacement) above a stable support surface are the most common in testing dynamic balance using an FP. Maximal range measures of voluntary body leaning in different directions is used within the limits of stability tests (Cameron & Lord, 2010), while the precision of dynamic control over COP displacement is tested using the so-called active COP tracking tests (Punakallio, 2004). Regarding the latter, the subject attempts to follow different reference COP trajectories with either self-paced (e.g. tracking static lines or shapes) or appointed dynamics (e.g. tracking moving curves), but in both cases with the highest possible precision. This methodological approach has been adopted from the open kinetic chain tasks where it has been used for years (Behm, 2004; Kurillo, Gregoric, Goljar, & Bajd, 2005; Maffiuletti, Bizzini, Schatt, & Munzinger, 2005).

Walking and running are the two main gaits in humans, both being forms of bipedal cyclic locomotion. During the stance phase of running/walking a complex three-dimensional dynamic loading of the supporting leg takes place. These loading characteristics vary across age (Lilley, Dixon, & Stiles, 2011), gait speeds (Chung & Wang, 2010), gender (Chiu & Wang, 2007), footwear (Keenan, Franz, Dicharry, Della Croce, & Kerrigan, 2011), etc. In addition to ***gait, other body transfer activities*** are functionally relevant (e.g. stopping, sit-to-stand and turning) and have been evaluated in science and medical/sports practice. Many of these tests have their origins in daily clinical practice, but they have been advanced by the measurements of the GRF, which enables studies of biomechanical aspects of leg-to-floor interaction. However, when performed at submaximal or maximal intensities, all these movements are also very relevant to sport performance (e.g. agility, running/sprinting and braking).

Fast alternating movements performed by either legs or hands have become a part of everyday sport performance assessment and also a window into some very basic researches in the field of motor control and behaviour (Smits-Engelsman, Swinnen, & Duysens, 2006). Most commonly used are the so called "stamping tests" (i.e. fast cyclic movements with the left and right extremity in anti-phase) and "tapping tests" (i.e. fast cyclic movements with one extremity aimed at two or more different targets) (Baldissera, Rota, & Esposti, 2008). If those tests are performed on an FP, several frequency-, force- and precision-related parameters can be calculated. These parameters can be observed in the context of time which can be applied either to fatigue development or to learning effects. Moreover, stamping tasks could be used to study the effects of gravitational loading on movement frequency (e.g. legs stamping in a seated vs. standing position), while tapping tasks could be used to study contralateral differences or speed/accuracy trade-off (i.e. increased speed of movement reduces its accuracy and *vice versa*) (Kuboyama, Nabetani, Shibuya, Machida, & Ogaki, 2005; Young, Pratt, & Chau, 2009).

The most often used anaerobic ***strength and power*** tests involve multi-joint extensions of the lower extremities (Capelli & di Prampero, 1991; Ziv & Lidor, 2010). This basic movement pattern can be performed either at moderate velocities (e.g. squats) or explosively (e.g. jumps). Jump tests basically differ according to the concentric (e.g. squat jump) or eccentric-concentric (e.g. counter-movement jump) type of muscle action. Functionally, they can also be divided into vertical and horizontal jumps. Additionally, the movement tasks used in the tests can require predominantly hip and knee action (e.g. squat jump and countermovement jump) or a predominant ankle action (e.g. drop jump and hopping) (Baca, 1999). In both cases a test can consist of either a single repetition or multiple consecutive repetitions, the latter being used in the assessment of endurance in explosive power (McCaulley, et al., 2007). Additional loading/unloading can be used in order to observe power:velocity relationships (Kraska, et al., 2009). FP measurements of the previously mentioned strength and power movement tasks enable detailed analyses of the GRF during take-offs and landings. Based on the force:time signal, quantitative analyses can be run in order to calculate numerous time, power, force impulse and COP indexes.

Last but not least, there is a constant need for research laboratories to perform non-standard measurements using their FPs. However, this is often a problem because of the software limitations and restrictions. Therefore, optimal FP software should enable the user to carry out a free acquisition of signals coming out of the FP, perform analysis and export data in different formats. This is namely the way how the development of new evaluation routines emerges and provides a new potential for the translation of science into practice.

Technical solution

The technical solution of MARS is based on the following conceptual structure: (i) central processing unit, (ii) management unit, (iii) test modules, (iv) comparison unit, (v) reporting unit, and (vi) database. The entire software is programmed in LabVIEW 2010 (National Instruments, Austin, Texas, USA). Figure 1 illustrates the data flow and the relations between the main software units. This concept provides MARS with all necessary data structures and functions for the three main tasks: measurement, analysis and reporting. The individual software functions are interrelated in such a way that the end user can carry out the process of measurement, analysis and reporting intuitively and easily. The operation of all MARS functions is well supported with extensive Help information including how-to examples. Moreover, each test is broadly explained in Help including: (i) a brief general description, (ii) performance variations (i.e. input parameters) presented graphically and explained in the text, (iii) test protocols, and (iv) a detailed explanation of the result parameters (descriptions, graphical visualizations and equations).

The MARS central processing unit communicates with all the other units and measurement modules enabling an easy and transparent execution of tests. It is programmed to carry out some basic functions such as weighing the subject, managing test settings, exporting the data (for backup; and all signals and results values in ASCII format) and indicating what measurements were performed.

The management module provides operational functions (add, edit, delete, assigning, searching and filtering) for the main entities: projects, visits and subjects. A project is the topmost entity that defines the conceptual naming of groups of tests to be carried out on a subpopulation (e.g. a football team that is to be tested for strength, power and balance). A project consists of visits and subjects. A visit defines one session of the project for a specified subpopulation (e.g. preseason/postseason) and a subject is a person defined with personal characteristics (name, age, height, profile, etc.). A project could have several visits and subjects. A visit is assigned exactly to one project and could have several subjects, while a subject could be assigned to several projects and several visits.

The test modules shown in Figure 2A, are different motor tests that are used to assess a subject's performance: (i) static balance (body sway), (ii) dynamic balance (shape tracking, curve tracking and limits of stability), (iii) locomotion (step analysis, forward lunge, sit-to-stand and turn), (iv) fast alternating movements (stamping and tapping), and (v) strength and power (squat, squat jump, counter- movement jump, drop jump, jumps with additional weights, long jump, repetitive countermovementjumps and repetitive hopping). A module for free measurements is available for custom tests. In all modules there are functions to export three types of data: raw signal in ASCII format, signals' graphs as an image in BMP format into clipboard (further it can be saved in any other format with an appropriate external application) and results values (with or without names and units) in ASCII format.

MARS test modules provide functions for easy execution of tests, including the definition of the input parameters, the acquisition of signals, real-time signal visualization, user feedback, analysis, visualization of results, and saving the data. Typical execution of the test is presented in Figure 2B. Some tests may have additional steps included. MARS also provides a function for comparing variations

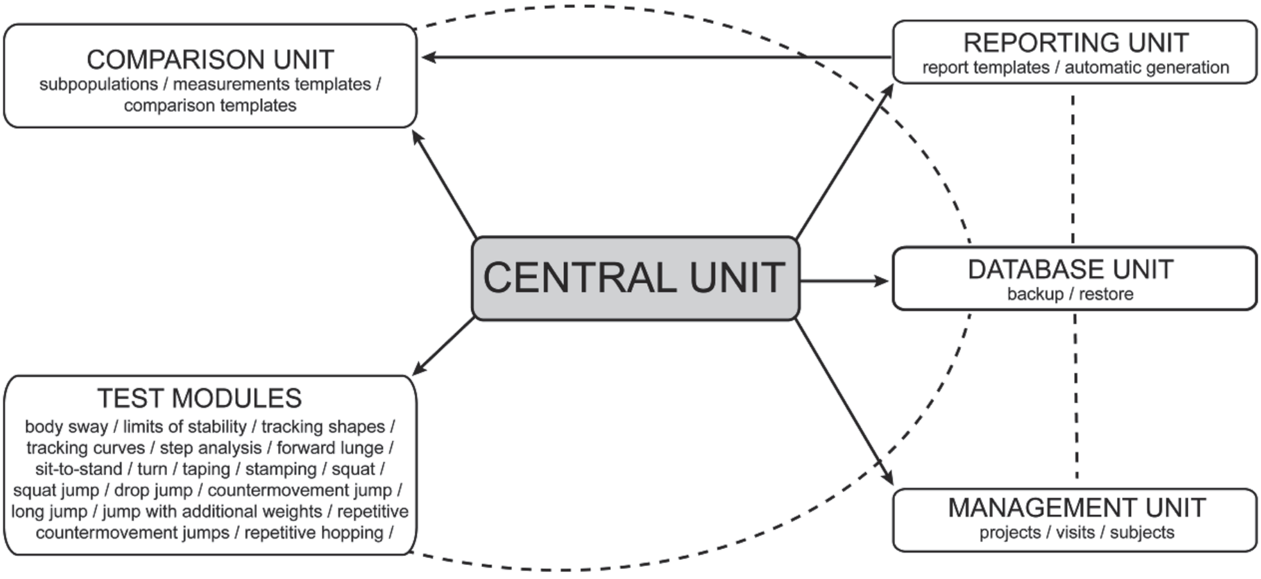

Figure 1. The conceptual structure with data flow and unit relations inside the software.

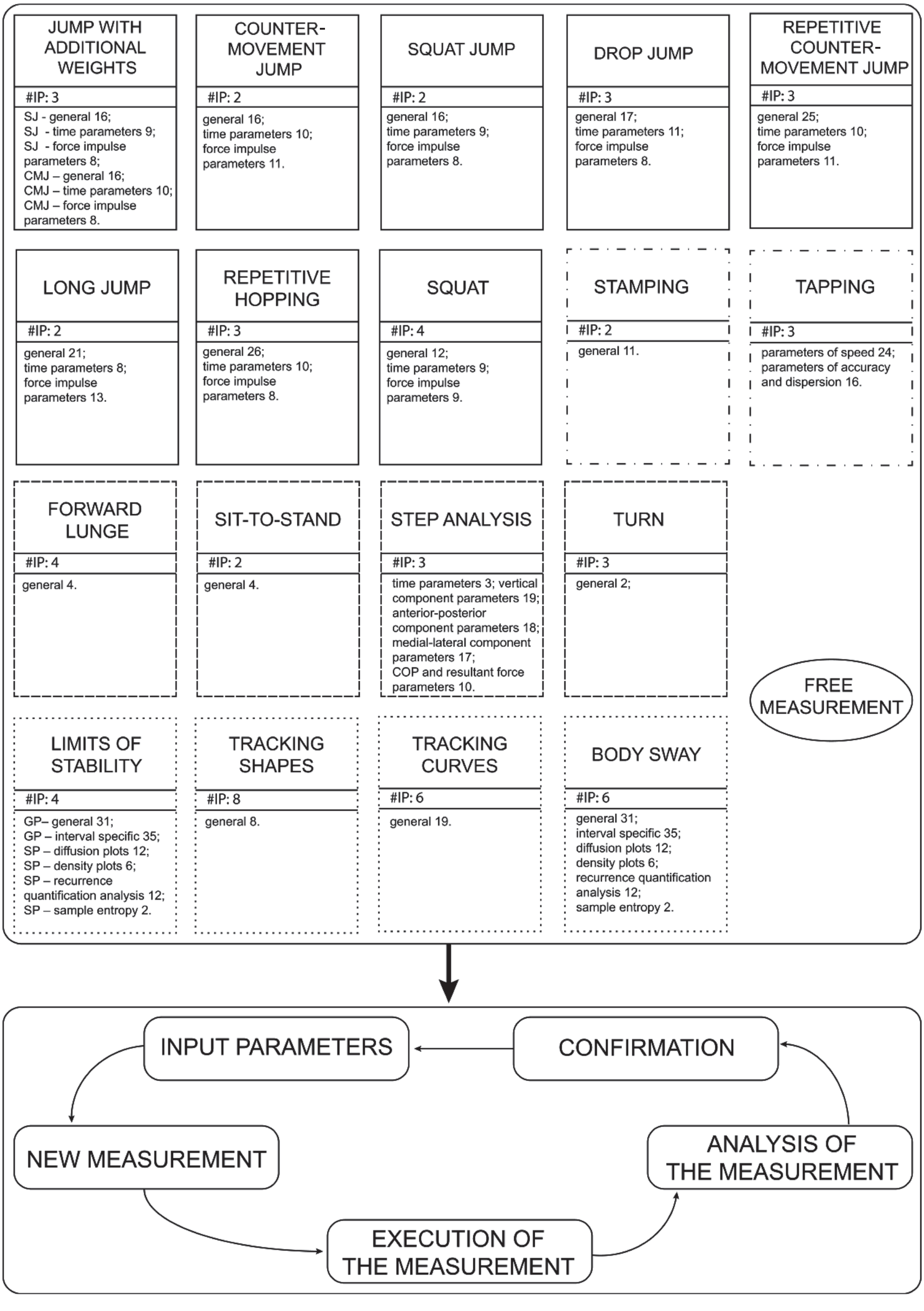

Figure 2. (A) Test units with name, number of input parameters (#IP) and groups of results parameters with the number of parameters. Different frames' lines denotate the groups of tests: solid line – power and strength, dash-dotted line – fast alternating movements, dashed line – locomotion and body transfer, and dotted line – balance. (B) Common execution steps of the test. Legend: SJ – squat jump, CMJ – counter movement jump, GP – global parameters, and SP – structural parameters.

of the test performed with a selected subject, for example, the comparison of performance between the left and the right leg.

The comparison module provides a variety of comparison types; for example, between the subject and subpopulation, between several subpopulations and between visits during a given project. A subpopulation is a group of subjects in a project whose database is used for making a comparison in results' parameters of a certain type of a test or of a group of tests. Four options for defining result parameters (on either a subject or subpopulation level) are available; namely, average, maximal, minimal and manually selected repetition. Comparisons can be expressed in either Z-values or relative values. For relative comparison an additional subpopulation (or a single subject) must be defined. Comparisons with previously described elements could be saved as a template and used in the reporting module for the automatic generation of reports.

The reporting module provides the functions required for the final step of subject evaluation. Its biggest advantage is the option to automatically generate reports for a selected subpopulation. The elements of the report are defined in a user-friendly editor with visual feedback of the specified content. A created template can be saved and used later for another subpopulation. Automatically generated reports can be edited with additional comments/notes or other elements (such as additional tables, images and graphs) and also some elements may be left out when not applicable.

The database module provides the functions for data manipulation and storage. They are automatically executed in the background and the user is not aware of it while working with the application. The database is based on a SQLite software library that implements a self-contained, serverless, zero-configuration, transactional SQL database engine, version 3.7.9. The integrity of the MARS database is assured by an embedded backup function with the ability to restore the database after a disturbance. This crucial requirement is commonly forgotten by users, but the loss of data after days or even months of work is probably one of the most unpleasant experiences for the scientist or practitioner.

In this brief presentation it was not possible to present all the details of the application. Other features have also been built into the concept to provide either further user support to the main functions or to improve user experience.

Conclusion

We believe that MARS can fill the lack of similar comprehensive solutions on the market and advance the field of biomechanics helping researchers and practitioners to exploit the full potential of their FPs. We have set a solid software foundation in which all the crucial functions have already been developed, that is, signal acquisition, storage, processing and quantification, comparisons and reporting. The software enables many different kinds of tests to be run and we see it as a base for future extension, improvement and upgrades. Moreover, further evaluation and validation of the MARS measurement modules shall be carried out at the final stages of the development process.

In the future, we plan to develop MARS in four different ways. First, all the existing test modules will be upgraded for bilateral FP measurements, where each foot is placed on a separate FP. In the majority of bilateral tests (e.g. jump, hop, squat, balance, etc.) this will widen the informational value of the measurements by enabling contralateral comparisons (i.e. asymmetries) to be made. Second, functions for multiple FPs measurements will be added with the aim of enabling the analysis of movements during which the body is predominantly horizontally translated (e.g. sprint start, take-off in ski jumps, track-and-field long jump, etc.). Third, we would like to increase the functional relevance and informational value of the FP tests by developing new sets of additions: (i) a set of visual markers, (ii) a set for simple loading/unloading of the subject, (iii) a set for simultaneous measurements of linear excursions, i.e. functional reach test, star excursion test; and (iv) a set for mechanical perturbations and sensory manipulations. Fourth, we will develop a server-based system with web access for the storage of the measurements. This will enable the storage of measurements from around the world in one central archive. In any case, this upgrade will be offered to the MARS users only as an optional choice. Those users who will decide so, in exchange will have access to a huge amount of data and, consequently, scientists and practitioners will be able to develop reliable normative values. Such an upgrade will also enable large scale research. However, we are well aware of the issues regarding personal data security, which we plan to address accordingly. Moreover, we are also aware of the need to control the quality of the measurements that are going to become a part of such a database. We therefore aim to consider additional control measures (e.g. video recordings of the tests, automatic recognition of outliers, etc.).

To summarize, in the near future we plan to finalize the current stage of the development of MARS for FP-based tests. Besides keeping on with the development, we will commence to attract suitable partners from industry to help us launch the product on the market, and thus, make a real translation from science to practice.

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RAZVOJ PROGRAMSKE PODRŠKE ZA SVEOBUHVATNU ANALIZU VARIJABLI DOBIVENIH MJERENJIMA POMOĆU TENZIOMETRIJSKE PLATFORME

Ovaj tehnički rad objašnjava razvoj softverskoga rješenja za prikupljanje i analizu podataka te oblikovanje izvješća o rezultatima testova provedenih na tenziometrijskoj ploči. U uvodu je predstavljen pregled povijesti razvoja tenziometrijskih platforma, nakon čega slijedi opis postupaka za prikupljanje i parametrizaciju rezultata mjerenja sile reakcije podloge. Drugi dio je kratak opis pet skupina testova na tenziometrijskim pločama za procjenu ljudskoga kretanja: (i) testovi statičke ravnoteže, (ii) testovi dinamičke ravnoteže, (iii) testovi lokomocije i aktivnosti transfera tijela, (iv) testovi brzih alternativnih pokreta i (v) testovi snage. Nakon toga slijedi glavni dio u kojemu je predstavljeno tehničko rješenje i koncepcijska modularna struktura softvera. Istaknute su glavne funkcije, a grafički su predstavljeni, u pregledu, svi testovi koje aplikacija podržava. Na kraju su istaknute neke ideje o daljnjemu razvoju i budućoj praktičnoj primjeni ovdje predstavljene programske podrške.

Ključne riječi: *biomehanika, testiranje, instrumentacija, izvještavanje*