SMART: software for advanced registration and visualization of human morphological, kinematics and motion data

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***Abstract*— This paper presents a software tool that allows real time registration for anatomically and biomechanically correct modeling of the human lower extremities. Automated registration of heterogenous data is performed: motion capture, electrogoniometry and computer tomography data. Interactive result adjustment is also available.**

***Keywords-component;* biomechanics, registration, motion capture, real-time.**

I. Introduction

Motion capture systems based on marker tracking are usually used to collect motion data (GAIT). Such method shows several sources of inaccuracies, mainly due to skin motion artifacts [1]. The other type of inaccuracy is from anatomical landmark palpation (determination of positions for markers).

More accurate data can be collected using in-vitro protocol: for example, 6-degrees-of-freedom (6-DOF) electrogoniometry (GONIO) and computerized tomography (CT). Unfortunately, in-vivo use of GONIO is limited. On the other hand, 6-DOF GONIO data could be used to enhance GAIT data results.

The method, implemented in the software presented in this paper combines all three data sources (GAIT, GONIO, CT) in order to produce validated and more anatomically correct motion modeling. It is described in the following section and referenced as registration.

A user interface allows customization of the data processing pipeline. Results are displayed via 3D rendering window and graphical representation of motion parameters. Additionally our tool allows to visualize anatomical landmarks, anatomical frames and includes a full environment modeling system. Optimization in code allows online generation of graphs.

II. Registration Process

Registration is a process of combining data given from different sources (GAIT, GONIO, CT) to obtain advanced modeling. The quality of the final model is directly dependent on the quality of the registration process. The implemented registration process uses a set of parameters that alter properties of the underlying algorithm (the latter is described below).

A. GAIT & GONIO data preprocessing

Numerical smoothing and fitting of the original GAIT data were performed using wavelet transformation and spline smoothing. Wavelet transformation allowed removing numerical noise in GAIT data. The first 6 entries were left after Fast Fourier Transformation (FFT) over 32 point range (the number of taken points have to be divisible by power of two to apply FFT algorithm). Spline smoothing allowed estimation of both first and second derivatives from both original GAIT and GONIO data. Such filtering was necessary to obtain smooth behavior for all available DOFs. Smoothing parameters for spline approximation were determined from the curves of joint flexion acceleration. Afterwards, the same parameters were applied for smoothing of the remaining DOFs. We used five independent DOFs for each human lower limb. Both hips were assumed to be pure ball-and-socket joints with the three rotational DOFs measured from GAIT data. Rotations in the three anatomical planes (i.e., flexion/extension - Fle/Ext, abduction/adduction – Abd/Add, internal/external rotation – Int/Ext) for the hip, and Fle/Ext for the knee and the ankle joints were taken from GAIT as the five independent DOFs of each limb. The three translations at the hip joint (i.e, anterior/posterior – Ant/Post, superior/inferior – Sup/Inf, medio/lateral – Med/Lat) were assumed to be zero, and the other two rotations plus the three translations at the knee and the ankle joints were taken from GONIO-based passive motion. In other words, the five time-histories for each limb from GAIT were used to synchronize *in vitro* joints by *in vivo* full limb kinematics. Though other GAIT DOFs were assumed unreliable for registration process, these DOFs will be included later in the final model from GONIO data after the primary registration took place.

B. Motion capture data scaling

In practice simultaneous CT, GAIT and GONIO data collection from the same subject is difficult since GAIT data are collected *in vivo*, whereas GONIO data are collected *in vitro*. CT also raises ethical issues. It introduces the necessity to register one data source to another. There are two possibilities for such registration: scaling of CT and GONIO data to GAIT data; scaling of GAIT data to GONIO. Since CT and GONIO data were more accurate the GAIT data were scaled.

The scaling procedure for lower limbs processing previously located anatomical landmarks (ALs) is based on the centers of both femoral heads (RFH, LFH) and centers of the posterior edge of both calcaneus (RCA, LCA). ALs palpation definitions were from [2]. A set of ALs positions for both GAIT and GONIO were defined and used to calculate the scaling factor for each limb. Scale factor of both sides was averaged to give the final factor for scaling of the pelvic motion data. [3].

C. Double step GAIT data registration

Now double step registration can take place. It consists of primary and advanced registration. More details can be found in [3].

During the first step (i.e. primary registration) we assumed that each side of lower human limbs has only five DOFs, so for each frame we have ten variables that define pose: three rotations from each hip and only flexion/extension from the knees and ankles.

Further registration process needs restoration of DOFs we previously excluded from our view. Previous numerical experiments showed that using regression least square polynomials of 5^{th} order gives proper approximation of subject passive motion data for both knees and ankles [3]. Such approximation was implemented in the software. Further fine-tuning of the approximation can be done to obtain most suitable solution.

Finally, taking into account five described above DOFs from GAIT data and regression formulas for GONIO data, we synchronized joint motions and produced primary registered model. Usually this registration leads to some discrepancy in the relative motion of the registered model. The final result of this approach is also sensitive to the quality of the motion of the hierarchy root (e.g. pelvis). So if the motion of any other link is more reliable then it can be used as root. To overlap these problems we applied on advanced registration method.

To improve results of the primary registration the advanced registration applies variation of GAIT data within the range of expected accuracy of measurements. These variations together with primary registration are used to satisfy the external constraints (e.g. relative feet to pelvis motion).

From a mechanical point of view such optimization problem can be seen as Inverse Kinematics. The number of independent variables is five, whereas we are trying to minimize difference in 6 DOFs. A solution was to use weighted vector norm to make particular DOF less important.

To solve the minimization problem numerically we used a combination of random search, to get proper initial value, and regular constrained optimization procedure. Following a frame by frame independent minimization we are obviously getting discontinue pose behavior per time. So a final smoothing on the joint or/and global level is a necessary step.

III. RESULTS

The above registration method was implemented during the SMART (Skeleton Motion Analysis and Registration Tool) project.

A. SMART structure

The SMART application is written in object-oriented C++ programming language. It consists of the following main parts:

- A user interface including menu and hot keys. That is the most platform depending module, so it is implemented and integrated in a way that simplifies possible porting to another platform in the future (currently target platform of application is PC with Microsoft Windows ® 2000/XP).
- External data exporting/importing module that allows reading different file formats and converting them into internal binary format of data representation for the computational and rendering modules. Hard disk storage of results is also possible.
- 3D rendering engine that utilizes DirectX API to achieve efficient 3D rendering performance. SMART is built using such engine to give maximum performance for user. Special optimization has been implemented.
- Computational module. These are routines that perform all general calculations over GAIT, GONIO and CT data. They store and process all data in computational effective format to optimize operation speed. Also this part contains large subpart for the above described registration.

B. Quality of registration

To test software GAIT, GONIO and CT data were collected [3]. SMART was used to register and visualize the 3D model and also to give graphical representation of motion parameter dependencies (the motion representation can be chosen by user: OVP, G&S etc.). Even in large joint zooming joint motion corresponds the current anatomical knowledge about human joint in both visual and numerical representations (e.g. plots synchronized to animation).

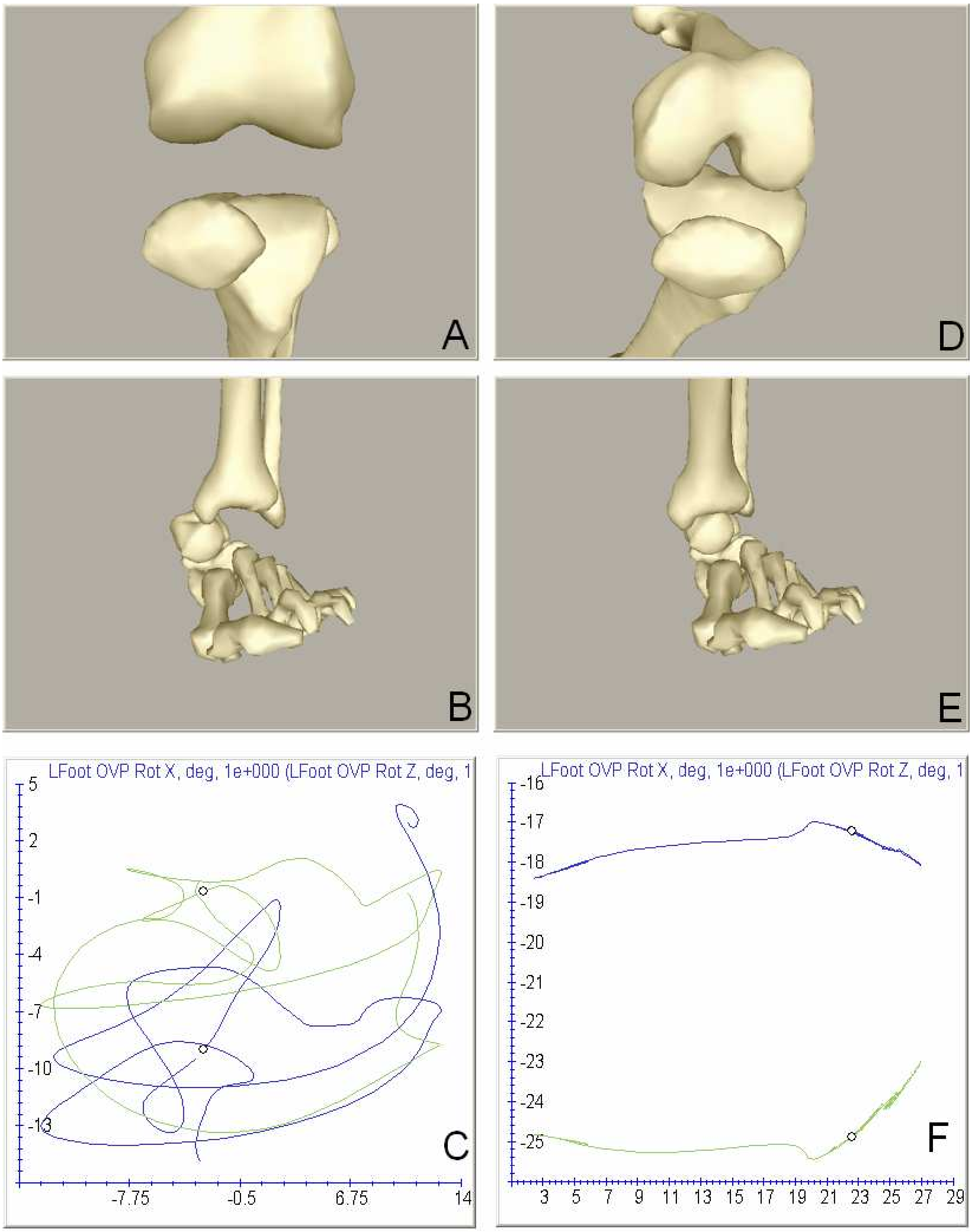

Figure 1. Left column: before registration. Right column: after advanced registration. A and C: visualization of left knee. B and E: visualization of left ankle. C and F: OVP representation of left ankle internal/external rotation and adduction/abduction from knee flexion. Results before registration (C) are obviously wrong. Advanced registration leads to anatomically correct motion representation (F).

The applied graphs and joint visualization snapshot show the joint behavior difference before and after registration process took place. Figure 1A illustrates left knee joint visualization before registration. Figures 1B and 1C illustrate left ankle joint visualization and angular motion dependencies before registration.

Figure 1D illustrates the left knee joint visualization results after registration procedure. Figures 1E and 1F illustrate left ankle joint visualization and angular motion dependencies after registration process. Given dependencies corresponds to well known ones described in biomechanical literature [4].

C. Performance achievements

Based on high performance 3D rendering engine SMART software allows to perform real time (30 fps) visualization of GAIT data using high-resolution bones. Total up to 300.000 triangles in the bone surface models are supported in real time animation on the Intel Pentium IV 1.6 GHz with nVidia GeForce 4 Ti4200, that is far from the currently top computers. Such performance is generally enough for educational and research purposes. It seems that for clinical use this may be not fast enough, but using currently available high performance systems especially with multi-kernel processors and using SLI technology in video systems (i.e. multiple video processors video processing technology) will enhance performance a lot.

IV. CONCLUSION

Several revisions of the SMART software have been made already (one of them is described in [5]). The latest version is described. It contains full implementation of double step registration [3]. Fig. 2 illustrates the SMART user interface that contains 3D rendering window with model being visualized, model visualization window, graphical representation of motion parameters window and customization window that allows user to setup visualization parameters.

Now we are working on integration of our software into Multimod Architecture Framework (MAF) and on extension of amount of parameters for optimization as well as on application to wider range of joints.

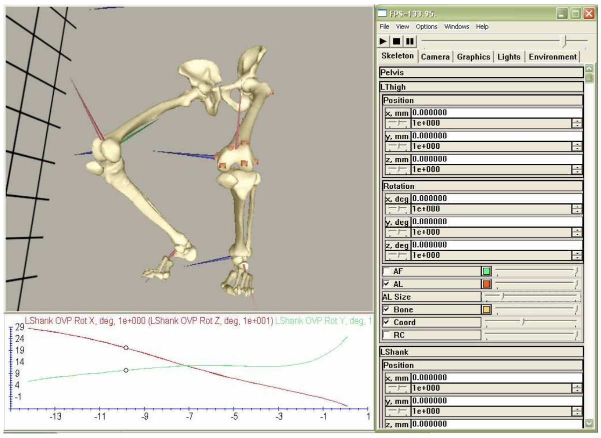

Figure 2. SMART software user interface.

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REFERENCES

[1] Cappozzo A., Catani F., Della Croce U., Leardini A. (1995) Position and orientation of bones during movement: anatomical frame definition and determination. *Clin. Biomech*, 10, pp. 171-178.

[2] Van Sint Jan S. Atlas of skeletal landmark definitions. Guidelines for accurate and reproducible palpation. Elsevier, Edinburg, In Press.

[3] V. Sholukha, A. Leardini, P. Salvia, M. Rooze, S. Van Sint Jan Double-step registration of in vivo stereophotogrammetry with both in vitro 6-DOFs electrogoniometry and CT medical imaging. J Biomech., (accepted for publication).

[4] Wilson D.R., Feikes J.D.,", Zavatsky A.B., O'Connor J.J. The components of passive knee movement are coupled to flexion angle. J Biomech 33, 465-473, 2000.

[5] V. Y. Aranov, V. A. Sholukha, S. Van Sint Jan Biomechanical analysis and visualization tool of human morphological and motion data. Graphicon, 2004.