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Uncertainty Evaluation of a Method for the Functional Reach Test Evaluation by Means of Monte-Carlo Simulation

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***Abstract* –The Functional Reach Test (FRT) is a simple, portable, clinically accepted tool that is used to measure semi-static balance. In a recent study, video recordings and software elaborationshave beenperformed by a computerized system to determinethe FRT objectively (computerized FRT, cFRT):here an in-depthstudy on the measuring error of the above system is proposed.Main uncertainty sources identifiedare (a) geometrical errorsdue to the alignment of the camera calibration plane with the real motion plane, (b) the difference in depth between the above planes, (c) the image aberration due to the lens that compress the pixels and (d) the software error in position estimation using a template matching algorithm. The uncertainty evaluation is performed by means Monte CarloSimulationsand results suggest that both the depth error and the barrel distortion are the more relevant source of error, althoughthe aberration can be corrected by one of the many algorithms available in literature. Results can be useful to define a measurement protocol to improve the performances of thesystem for a better clinical effectiveness.**

Keywords – Uncertainty, Functional Reach Test, Monte Carlo Simulation, distance measurement, image analysis

I. INTRODUCTION

The Functional Reach Test (FRT) is a clinically accepted tool forassessing semi-static balancein the anterior–posterior direction. It is particularly useful for elderly people and for patients affected by neurological diseases, e.g. vestibular disorders, physical decline, stroke, Parkinson's disease, etc. In particular it aims to measurethe maximum displacement achievable by stretching one arm withoutlosing the balance or stepping (Functional Reach FR).

The functional and cognitive decline in elderly people may have negative effects on their quality of life, due to the decrease of physical performances, as well as falls and hospitalizations [1], therefore its assessment is important [2-5]: several clinical tests have been designed to assess balance and mobility and FRT has been used to demonstrate both physical performances and cognitive functions decrease with aging [6, 7]. In particularthe FR is usually evaluated through an operator observing the arm displacement on a tape [8,9]: the lack of any specific instrumented device and the operator dependency make the test very low repeatable. Therefore, as for other diagnostic applications in various medical fields [10-17], in a recent study video acquisition and processinghas been applied by means of a computerized system to make the FRT more objective (cFRT)in order to improve both the measurement repeatability and the diagnostic effectiveness [18]. Moreover,a preliminary validation of the above system has been assessed in [19] by means of a calibrated stereo-photogrammetric system: the percentage variation between the two systems is lower than 3% in all subjects (4 healthy men, 10 trials each one)and it is significantly lower than the percentage variation obtained in daily clinical practice.As a consequence of the encouraging results, in the present work an in-depth study on the sources of uncertainty is proposed and appliedby means of a Monte CarloSimulation (MCS).

II. UNCERTAINTY IDENTIFICATION

The system under study is made up of a webcam that captures the patient motion and software to process the data for the FRT estimation (Fig.1). In particular:

1. Animage acquisitiondevice forpatient motion recording and transmission to the processing unit. This component can be a webcam or an equivalent opto-electronic system.
2. A processing unit (i.e. a desktop PC)where a template-matching algorithm isimplemented toautomatically determine the fist's trajectory in the recorded video of the patient.

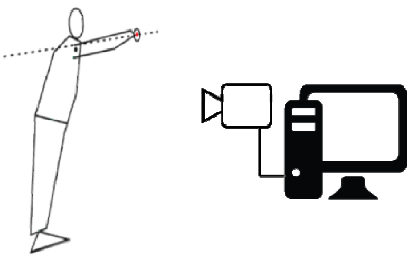

Fig. 1. Measurement system equipped with a webcam to acquire the patient motion and a PC for the template matching analysis to determine the fist displacement in the video.

The above system is quiteuser friendly and can be applied in most of the common clinical environments for a preliminary FRT evaluation,neverthelesssome sources of error should be considered and quantified for a correct interpretation of the results.They can be classified in two main groups:

1) Optical and geometrical errors: as in other applications where the transducer ismanually fixed or aligned without instrumentation [20,21], it is important to evaluate the uncertainty sources that came from (a) the relative orientation of the camera with respect to the patient's plane and (b) the image distortion caused by the optical deformation of the lens (aberration error). The difference in distance from the camera between the motion plane of the patient and the plane used duringthe system calibration (depth error).2) Software error: errors due to the use of a software that implemented a template matching algorithm to follow the fist movement into the scene.

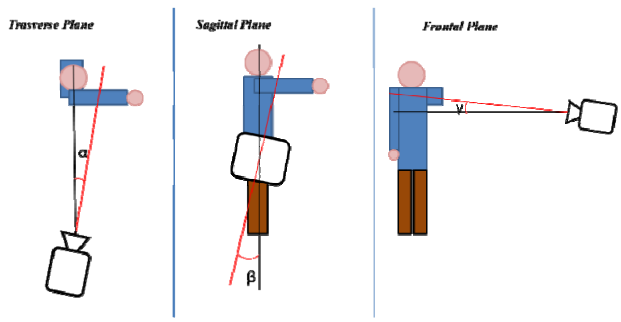

Fig.2. Angles errors related to the 3 planes of the space during the camera placement: α in the transverse plane, β in the sagittal plane (motion plane) and γ in thefrontal plane (tilt); the theoretical and actual orientation are reported in black and red respectively

III. DESCRIPTION OF THE METHOD

In this section,the main sources of error above mentioned are described and quantified. Optical and geometrical errors are modelled witha geometric deformation of the actual FR distance as in (1):

(1)

Where FRm is the FR seen by the camera, FRr is the actual FR, α, β and γ are the angle in the transverse, sagittal and frontal plane respectively (fig.2). From the (1)it can be observed that anglesα, β and γ provide an underestimation of the actual FR :this parallelism error has been here estimated±5° (for each angle) with a uniform probability distribution, like in other applications the camera alignment is provided manually.The difference in distance from the camera between the calibration plane and the motion plane (depth error) is another source of error, whose contribution $e_{\%}$can been estimated from Fig.3 and the following expression (2):

(2)

Where FRf is the functional reach measured from the image when the actual motion plane is at distance d from the calibration plane and at d+D from the camera.

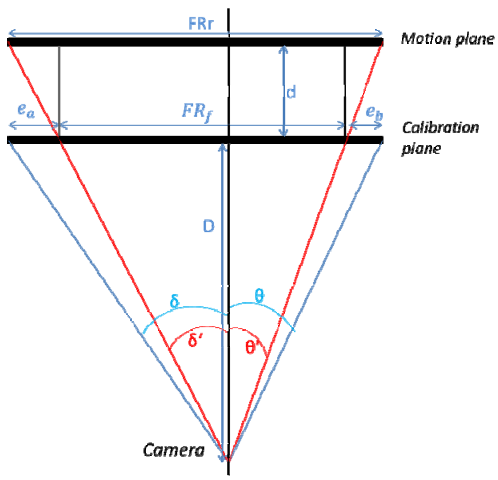

Fig. 3.Depth error between the calibration and motion plane: FRr is the actual FR and FRf is the FR measured from the image, d is the distance of the motion plane from the camera calibration plane. and are the difference between the FR on the calibration plane and the same FR on the motion plane, they are the length that is lost in the edges projection effect..

inthe MCS[22] we consideredthis kind of error uniform distributed between -10 cm and +10 cm and expressed as single standard deviation. Since $e_{\%}$ is also a function of the distance D of the calibration plane,ithas beenevaluated for different values of D (table 1):

Table1.Maximum e% at different distances D.

	2 m	3 m	4 m
e%	4.8%	3.2%	2.44 %

From table 1 the highest value of e% is used to model the depth error in the MCS witha uniformly distributed uncertainty of 4.8%. The barrel aberration error is produced by the image distortion due to the spherical projection of the camera lens and, since the transverse magnification decreases with axial distance, each image point moves radially towards the center of the image. This effect can be modeled as an exponential function proportional with the distance of the point to the center[23-26]. On the other hand the software error sourceis mainly related to the uncertainty of the position estimation that affects the template matching algorithm output.With the aim to evaluate the above contribution some MCSs are performed on a custom image where the positions of the targets are fixed: the application of an aberration distortion to the original image, allow the estimation of the difference between the measured (distorted) and the actual displacement. From expressions (1) and (2) both the contribution to FR uncertainty are considered in (3):

(3)

In the next section the expression (3) is used to evaluate the uncertainty of the whole systemby means of MCS.

IV. RESULTS AND DISCUSSIONS

From the MCS application to the system model(n=10000 iterations) we obtain the distributions in Fig. 4, fig. 5 and fig. 6. The simulations are done considering two cases: (a) motionat the edge of the image (the left side is chosen for similarity with the real recording) (b) motion into the image center. In Fig. 4, the FR distribution of a 200 pixel displacement is shownin the case (a), the distribution is obtained only considering the software error. Considering the source of errors modeled in (3), in fig. 5 the FR distributionsare shown without implementation of the barrel deformation of the lens for both cases (a) and (b). Finally, for a barrel distortion in the image (distortion coefficient $5\cdot10^{-7}$[23]),.the FR distribution is shown in fig.6.All the results are summarized in Table 2.

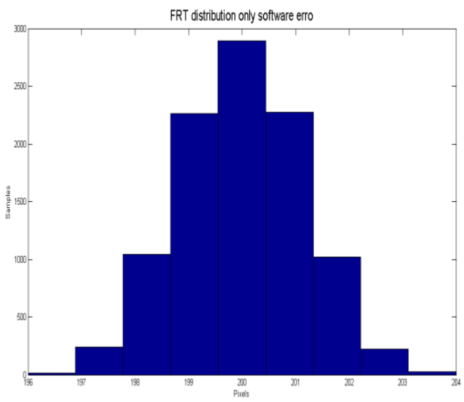

Fig.4.Example of FR's distribution due to software error only (no barrel distortion)

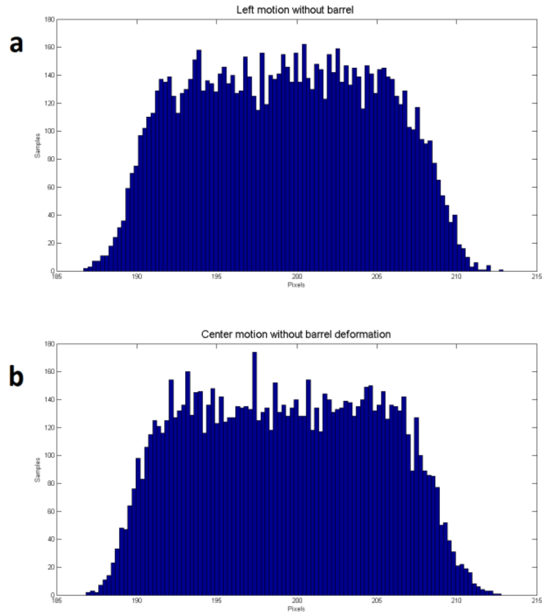

Fig.5. Example of FR's distribution without barrel deformation for a motion at the edge of the image (a) and at its center (b) .

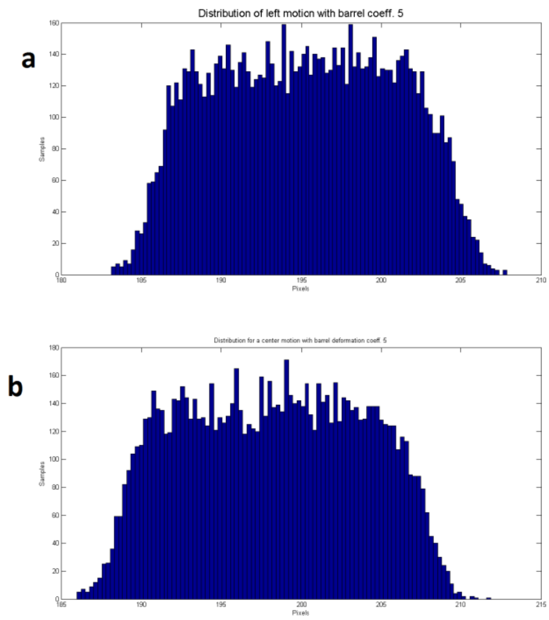

Fig.6. Example of FR's distribution with barrel deformation's coefficient of 5·10-7 for a motion at the edge of the image (a) and its center (b) .

The FRm distributions are very similar in the undistorted cases, i.e. the same mean valueFR_m and standard deviationσ_{FR}. On the other hand, in the barrel distortion images they have the same standard deviation but a shifted mean value,likely due to the distortion of the image at the edge: indeed further experiments show that the greateris thebarrel distortion thehigheris the shift of the mean value, nevertheless the distribution shape looks the same, as suggested by the ratio σ_{FR}/FR_m From percentile upper and lower limits the uncertainty can be obtained at 95% of confidence level: for all the distributions (distorted and undistorted cases)a coverage interval of about5% is determined.

Table2.MCS results (10000 trials).

	Motion on left			Motion on center		
	No barrel	Barrel .5	Barrel.7	No barrel	Barrel.5	Barrel.7
Mean ValueFR_m	199	195	193	199	198	198
Standard Deviationσ_{FR}	6	6	6	6	6	6
Percentile lower limit(95%)	190	186	184	190	189	188
Percentile upper limit (95%)	209	205	203	209	208	207
σ_{FR}/FR_m	0,03	0,03	0,03	0,03	0,03	0,03

V. CONCLUSIONS

In this work a study on the identification and evaluation of the measurement uncertainty sources is proposed for an optic system for the FRT evaluation. The results showa relative uncertainty of about5% for a measurementat 2m from the camera (95% confidence level) and a shift of the mean value due to the barrel distortion that can be corrected with one of the common algorithms available in literature[23-26].Although in this work a contribution is given to the study on the most important sources of uncertainty in the optical set up for a FRT application, more studies are going to be conducted to investigate on the template matching errors by means of a software code analysis, in order to increase the robustness of the diagnostic method and its reliability.In particular, such activities will comprehend the assessment of more sophisticated template matching techniques [27-29] that could simultaneously satisfy an error reduction and a limited computational complexity

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