KINEMATIC, DYNAMIC AND ELECTROMYOGRAPHIC ANALYSIS OF FUNCTIONAL REACH IN DIABETIC SUBJECTS

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Abstract

The present study was based on the analysis of a specific motor task, the Functional Reach (FR) Test, used in the clinical practice to identify elderly subjects at risk of recurrent falls. Functional Reach has been defined as the maximal distance one can reach forward beyond arm’s length while maintaining a fixed base of support in the standing position. As shown in literature, the clinical FR measure cannot be considered as a measure of dynamic balance because it is not able to differentiate between healthy elderly people and individuals with balance impairments. More information can be obtained from this motor task by looking in more detail at the kinematic behaviour, at the motor strategies employed and also at the electromyographic activity pattern.

The study is composed of two parts: the first one is focused both on the description of the principal kinematic parameters that characterise this motor task and also on the investigation of the motor strategies used during the test. The second one deals with the electromyographic analysis of specific muscles of the body to understand the timing of the muscle activity during the Functional Reach Test. The study was conducted on non-neuropathic and neuropathic diabetic subjects.
Results highlight how similar FR values can be obtained by different movement strategies. While for diabetic non-neuropathic subjects, FR is mainly performed by trunk flexion in the sagittal plane, for diabetic neuropathic patients, FR is also significantly accomplished by trunk rotation in the horizontal plane. When reaching forward with one arm, as in the FR test, although a great part of movement occurs in the sagittal plane, rotational movements in the transverse and coronal planes also occur and cannot be disregarded. From the electromyographic point of view, neuropathic and non-neuropathic diabetic subjects show a similar behaviour, with the anticipatory activity of tibialis anterior, necessary to move the centre of pressure backward and to give rise to the ankle dorsi-flexor moment able to unbalance the body forward. The difference is in the timing of this muscle activation: in fact, in diabetic neuropathic patients, the tibialis anterior is activated earlier than in non-neuropathic subjects.
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Chapter 1.

Introduction

Falls are a leading cause of disability, injury and death in older people and represent a major public health problem with substantial medical and economic consequences [1.1]. In Italy, every year more than 3000 people die in their homes due to falls and, according to ISTAT and INAIL data, every 10 seconds a domestic incident occurs that requires hospitalization. In 2007, femur fractures caused by a fall, were about 8000 at a cost of more than €250 million. Falls in the elderly increases with advancing years. 35 40% of patients older than 65 years fall at least once a year and the incidence is much higher in the elderly with more than 75 years. According to ISTAT data, in Italy the elderly with more than 60 years are currently about one-fifth of the total population (11 million) and people aged less than 85 years are about a million and a half, and those with more than 100 years are over 12,000. Now, life expectancy is 77.1 years for men and 83.2 years for women. The significant increase in the elderly population and the increase in actual damage that the projections (33.7 in 2050) justify the attention they need to address the phenomenon of the fall, in order to implement an appropriate strategy to limit the number, severity and costs economic and welfare [1.2].
Several studies foresee that the numbers of persons aged 65 years and older will be more than double by 2030 and the number of persons aged 80 years and older will increase by more than a factor of five by 2050 [1.3].

The rate of falls increases with age. In particular, it was reported [1.4] that 13% of adults aged 65-69 years, 14% of those aged 70-74 years, 16% of those aged 75-79 years, and 21% of those aged 80 years and older fell during 3 months preceding the survey (Fig. 1.1).

![Bar chart showing percentages of falls in elderly groups](image)

**Figure 1.1.** Percentages of falls in a group of elderly. The rate of falls increases with age. [1.4]

Nearly one third of people aged 65 years or older fall each year with consequences ranging from mild to severe disability. One half of these patients fall more than once. The risk of falls increases substantially with age, as does the risk of serious injury with each fall. Approximately 10% to 15% of falls result in serious injuries,
and unintentional injuries are estimated to be the fifth most common cause of death in older adults. Many serious injuries are due to fractures, most notably hip fractures, and up to 75% of hip fracture patients will not regain their prior level of function. Patients hospitalized for a fall are also at high risk for subsequent disability and nursing home placement. Other serious consequences of falls include head injuries, pain, restriction of mobility, fear of recurrent falls, depression, and social isolation. Fear of falling can be a particular problem for older patients. Patients who fall, often limit their activity, which leads to further functional decline, muscle weakness, disability, and risk of further falls [1.5].

From this short introduction it is evident as falls among older people thus remain a very important public healthcare issue.

1.1 DEFINITION, RISK FACTORS AND CAUSES OF FALLS

1.1.1 Definition of fall

It is particular important to have a clear and a simple definition of ‘a fall’: even if everyone intuitively knows what a fall is, when asked to define it, people struggle for words. Morris and Isaacs (1980) define a fall as “an untoward event in which the patient comes to rest unintentionally on the floor.” But this definition
remains problematic for clinicians. Has the patient fallen if the patient is “caught” and lowered into a chair? Is it considered a fall if the patient grabs a handrail and does not land on the floor [1.6]? It is evident as the definition of a fall became a need for different researchers, in order to clearly identify which events could be included and which could not, and to classify different types of falls in order to allow the comparability between research results. A recent consensus statement (ProFaNE, Prevention of Falls Network Europe) defines a fall as "an unexpected event in which the participant comes to rest on the ground, floor, or lower level" [1.7]. The proposed operational definition of a fall should maximize the likelihood that elderly people report all falling events.

1.1.2 Risk factors

Fall incidents and the ensuing injury process are multifactorial process, including long-term or short-term predisposing factors, which may be modified by age, disease, and environment. The factors responsible for falls can be classified as intrinsic (physical and cognitive factors) and extrinsic (external factors):

- **INTRINSIC FACTORS**: physical and mental changes related to ageing (but not associated with disease), neurological disorders (stroke, transient ischaemic attack, parkinsonism, cerebellar disorders, peripheral neuropathy,
dementia), cardiovascular disorders; metabolic disorders (hypothyroidism, hypoglycaemia), musculoskeletal disorders (muscle weakness, gait and balance impairment, arthritis, proximal myopathy), psychological disorders (depression, anxiety), modifications of vestibular, proprioceptive and visual functions, medication use.

✔ EXTRINSIC FACTORS: classified as environmental factors (obstacles in a path of travel, poor lighting, slippery floors, uneven surface, footwear, clothing) and behavioural factors (activities and choices that can destabilize balance, such as running or wearing improper shoes, inappropriate walking aids or assistive devices) [1.1].

At a population level, female gender, history of precedent falls and social isolation, along with increasing age, represent important risk factors for falls. In fact, functional capacity may decrease with age due to physical and mental changes that lead to impairments in balance, gait and strength. In addition, short-term memory loss, transfer assistance, urinary incontinence, positive fall history, use of trunk restraints were indicated as predictors of falls. In particular, a positive fall history was associated with frequent falls.

Some of these factors cannot be changed, but they are important indicators to define the classes of risk.
1.1.3 Causes of falls

There are many distinct causes for falls in old people [1.8, 1.9].

- ‘Accidental’ or environment-related is the most frequently cited, accounting for 30–50% in most series. However, many falls attributed to accidents really stem from the interaction between identifiable environmental hazards and increased individual susceptibility to hazards from accumulated effects of age and disease. Older people have stiffer, less coordinated and more dangerous gaits than do younger people. Posture control, body-orienting reflexes, muscle strength and tone, and height of stepping all decline with ageing and impair ability to avoid a fall after an unexpected trip or slip. In old age, the ‘strategy’ for maintaining balance after a slip, shifts from the rapid correcting ‘hip strategy’ (fall avoidance through weight shifts at the hip), to the ‘step strategy’ (fall avoidance via a rapid step), to total loss of ability to correct in time to prevent a fall. Age-associated impairments of vision, hearing and memory also tend to increase the number of trips and stumbles.

- The broad category of gait problems and weakness is the next commonest specific precipitating cause for falls (10–25% in most series). The ability to walk normally depends on several bio-mechanical components, including free mobility of joints, particularly in the legs; appropriate timing of muscle action;
appropriate intensity of muscle action; and normal sensory input, including vision, proprioception and vestibular system. Gait and balance problems have many aetiologies, and many therapeutic approaches can be effective. Readily identifiable gait problems adversely affect function in 20–40% of people aged >65 (and 40–50% of those aged >85), and about half of these problems are severe. In a large longitudinal study of persons aged ≥75, 10% needed assistance to walk across the room, 20% were unable to climb a flight of stairs without help, and 40% were unable to walk half a mile [1.10]. Gait problems can stem from simple age-related changes in gait and balance as well as from specific dysfunctions of the nervous, muscular, skeletal, circulatory and respiratory systems or from simple weakness following a period of inactivity.

✔ The next major reported cause of falls is dizziness, which is an extremely common symptom among older persons. However, it is a non-specific symptom and may reflect problems as diverse as cardiovascular disorders, hyperventilation, orthostasis, drug side-effect, anxiety or depression. The related problem of orthostatic hypotension, defined as a drop of over 20 mmHg of systolic blood pressure between lying and standing, has a 10–30% prevalence among ‘normal’ elderly people living at home. It can stem from several factors, including autonomic dysfunction (frequently related to age, diabetes or brain damage), low cardiac output, Parkinsonism, metabolic and endocrine disorders,
and medications (particularly sedatives, antihypertensive and antidepressant drugs). The orthostatic drop may be more pronounced in the morning, because the baroreceptor response is diminished after prolonged recumbency. However, it is a less common cause of falls than its prevalence would indicate, probably reflecting the fact that most persons with this syndrome become accustomed to it and are able to find a seat or adjust before falling [1.18, 1.19].

Drop attacks are defined as sudden falls without loss of consciousness or dizziness and, in the past, have been implicated in between 1 and 10% of falls. Patients typically experience abrupt leg weakness, sometimes precipitated by sudden head movement. The weakness is usually transient but can persist for hours. This syndrome has been attributed to transient vertebrobasilar insufficiency, although it probably stems from diverse mechanisms, including leg weakness and knee instability. Drop attacks are today reported much less often probably reflecting better diagnostic precision. In the past, the drop attack category was often used as a ‘waste basket’ category for otherwise unexplained falls. In reality, true drop attacks are quite uncommon [1.18, 1.19].

Syncope, or sudden loss of consciousness, usually results from decreased cerebral blood flow or metabolic factors. It has been the attributable cause of between 2 and 10% of falls in several series but has been excluded from many other series either by definition (because syncope is not a typical type of fall) or
because many elderly patients with syncope are acutely hospitalised and are treated differently [1.18, 1.19].

✓ Other specific causes of falls include history of falls, disorders of the central nervous system, cognitive deficits, poor vision, drug side-effects, alcohol intake, anaemia, hypothyroidism, unstable joints, foot problems, severe osteoporosis with spontaneous fracture and acute illness.

Because most elderly individuals have multiple identifiable risk factors predisposing to falls, the exact cause can often be difficult to determine. The figure 1.2 summarizes the major causes and the most common effects due to the falls.

Figure 1.2. Causes and effects of falls.
1.2 PRACTICE FOR FALL RISK ASSESSMENT

Falls among older adults are prevalent and preventable. In the absence of evidence to support a population-based approach towards prevention and the imperative to deliver cost-effective and efficient services, health care providers need risk assessment tools that reliably identify at risk populations and guide intervention by highlighting remediable risk factors for falls and fall-related injuries. Such tools typically consist of a rating or scoring system designed to reflect the cumulative effect of known risk factors. Recently, instrumental tools were developed to help the clinical practice for fall risk assessment.

1.2.1 Clinical tests for fall detection

Clinical tests for assessing fall risk in older persons with minor functional problems are several:

- TIMED UP AND GO (TUG) TEST: this test measures, in seconds, the time taken by an individual to stand up from a standard arm chair (approximate seat height of 46 cm, arm height 65 cm), walk a distance of 3 meters (approximately 10 feet), turn, walk back to the chair, and sit down again. It is a
simple test for evaluating one's ability to perform a sequence of basic activities [1.11].

✓ SIT TO STAND TEST: the test consists in standing up and sitting down 5 times as quickly and safely as possible [1.12].

✓ TURN 180°: the subject stand up and, on request, turn to face the opposite direction, without holding on to chairs, if possible [1.13].

✓ TINETTI SCALE: Tinetti assessment is a physical task-oriented scale which measures the gait and balance activities of older persons [1.14].

✓ BERG BALANCE SCALE: this scale is useful to rate the ability of an individual to maintain balance while performing the activities of daily living (ADL). Components include balance, lower and upper extremity strength [1.15].

✓ DYNAMIC GAIT INDEX: this scale consists of eight items and it is able to highlight the ability of the subject to modify gait in response to changing task demands like speed, step width and dual task condition [1.16].

✓ FUNCTION REACH TEST: it is defined as the maximal distance one can reach forward beyond arm’s length whilst maintaining a fixed base of support in the standing position [1.17].
Despite the fact that all these scales are portable, inexpensive, feasible for clinicians and acceptable to patients, these methods often depend on individual observation and subjective interpretation, and are also affected by the ceiling/floor effect. So, whereas they are able to correctly identify both healthy subjects and those at high-risk of fall, they are unable to identify subjects whose performance is placed between these two extremes [1.18].

1.2.2 Technologies for fall risk assessment

Human movement analysis aims at gathering quantitative information about the mechanics of the musculo-skeletal system during the execution of a motor task. In particular, information is sought concerning the movement of the whole-body centre of mass, the relative movement between adjacent bones or joint kinematics, the force exchanged with the environment and the muscular activities. The quantities that provide the above movement quantities are either measured or estimated using mathematical models of the musculo-skeletal system. In this way, quantitative descriptions of the functions of the motor system and of their changes, and/or of the way an individual executes a motor activity are obtained.

Classical approaches for the quantitative assessment of human kinematics and kinetics during the execution of clinical motor tasks are based on:
STEREOPHOTOGRAMMETRIC SYSTEMS: they are used in order to obtain the position of markers located on the skin surface using stereophotogrammetric methods (motion capture); it is then possible to derive both the information on how the movement is performed and on the linear and angular parameters, related to velocities and accelerations of body segments [1.19].

FORCE PLATFORMS: they are used in order to measure at each sampling instant the ground reaction force and the position of its point of application (Centre of Pressure, COP) [1.20].

ELECTROMYOGRAPHIC SYSTEMS: they are used to record the electrical activity of selected muscles [1.21].

It is not clear which tool or assessment instrument is the most predictive and therefore useful, but the need of objective, cost-effective and clinical applicable methods is evident. In fact, instrumented tests would enable quantitative assessment of fall risk on a specific subject, overcoming the limitations due to the lack of objectiveness related to individual judgement by a therapist or a nurse who report a score related to the physical performance.
1.3 **AIM OF THE THESIS**

In the light of the foregoing considerations, the attention has been focused on the study of a simple, yet significant, clinical test, the Functional Reach (FR) Test, using the instrumentation described above, i.e.: a stereophotogrammetric system, a force platform and a surface electromyographic system. This analysis was conducted on two kinds of subjects: diabetic and diabetic neuropathic patients.

A quantitative description of this motor task provides additional information which is not clearly visible by the clinician who monitors his/her performance. Even if balance scale provide indications about the ability of the subject to perform the motor task, more information can be obtained by looking in more detail at the kinematic behavior, the motor strategies employed and the muscles activation modalities.

The next Chapter is divided in two sections: the first one describes the kinematic strategies used during the FR task by the analysed subjects; the second section is mainly focused on the different modalities of leg and trunk muscles activation during the test.
Chapter 2.

KINEMATIC, DYNAMIC AND ELECTROMYOGRAPHIC ANALYSIS OF FUNCTIONAL REACH IN DIABETIC SUBJECTS

2.1 FUNCTIONAL REACH TEST: MOVEMENT STRATEGIES IN DIABETIC SUBJECTS

As introduced in Chapter 1, initially the Functional Reach Test was analysed from a kinematic point of view, in order to evaluate the movement strategy adopted during the task by diabetic and diabetic neuropathic subjects.

2.1.1 Introduction

The Functional Reach Test developed by Duncan et al. [1.17] has been proposed as a measure of balance able to identify elderly subjects at risk of recurrent falls.
Functional Reach (FR) has been defined as the maximal distance one can reach forward beyond arm’s length while maintaining a fixed base of support in the standing position (Figure 2.1).

![Functional Reach (FR) Test](image)

Figure 2.1. Functional Reach (FR) Test.

It is based on the idea that to investigate limits of stability in the absence of external perturbations, the maximum, voluntary, inclined posture can be used. In fact, limits of stability, quantified by the maximum, intentional displacement of the body in a given direction without losing balance, are influenced by body biomechanics as well as by subjective perception, and internal postural control abilities. So, a greater reach distance indicates a larger limit of stability and hence better dynamic balance ability [2.1]. In particular Duncan et al. [2.2] concluded that a reach distance smaller than 6 inches (i.e. 152 mm) is strongly correlated with high fall risk in individuals aged 70 years or older.
In clinics, FR is measured using a yardstick secured to the wall at the height of the acromion, and it is a simple, fast, and clinically well accepted test. It has been demonstrated to be precise (coefficient of variation = 2.5%) and stable (intraclass correlation coefficient across days = 0.81); it is portable, inexpensive and reliable [1.15]. It can be used as a marker of physical frailty [2.3] and as a useful measure for healthy elderly people [2.4, 2.5], patients following a stroke [2.6], with vestibular dysfunction [2.7], and Parkinson’s disease [2.8]. Age and height influence FR [1.15]. In addition, FR is also affected by the speed at which the motor task is performed [2.9, 2.10] and by the ceiling/floor effect: whereas it is able to correctly identify both healthy subjects and high-risk subjects (extremely unstable and at high risk of falls), it is unable to distinguish subjects whose performance is placed between these two extremes. This problem is common to many other functional evaluation scales.

A similar motor task, the Standing Reach (SR), has been proposed, too [2.10]. It differs from FR just because the reach movement is performed not only with the dominant arm but with both arms extended (Figure 2.2). Recent studies [2.11, 2.12] have been conducted to investigate which reach-test better reflects the centre of pressure (COP) excursion, either a 1-arm reach (i.e. the FR) or a 2-arm reach (i.e. the SR). The conclusion was that to evaluate the ability to maintain equilibrium in response to either self-motivated or external perturbation, FR is more valid than
SR. In another study [2.13] it was suggested that not only the COP, but also the kinematics associated with the SR test should be investigated fully to determine the balance ability.

![Figure 2.2. A. Functional Reach Test; B. Standing Reach Test.](image_url)

As shown in Wernick-Robinson et al. [2.14], the clinical FR measure, i.e. the maximal hand displacement, cannot be considered as a measure of dynamic balance because it is not able to differentiate between healthy elderly people and individuals with balance impairments. More information can be obtained from this motor task by looking in more detail at the kinematic behaviour and also at the motor strategies employed [2.14, 2.16-2.18]. In fact, upper trunk movements are accompanied by hip and knee movements in opposite direction, resulting in a reduced displacement of the centre of gravity (COG) [2.9, 2.19, 2.20].
It has been noticed that different strategies are used to accomplish this motor
task [2.14]. The problem is to define and determine the different motor strategies
employed and to analyse their consequences on specific movements.

The purpose of this study was to describe the principal parameters that
characterise the FR test in non-neuropathic and neuropathic diabetic subjects. This
latter category of patients exhibits a reduction of tactile and proprioceptive
sensibility and therefore a high risk of fall with respect to non-neuropathic patients.
The second goal was to investigate the presence of different motor strategies used
by these two classes of subjects. In order to achieve this aim, three different
movement strategies were defined, namely: “hip”, “mixed”, and “trunk rotation”
strategy.

2.1.2 Materials and Methods

Subjects and experimental protocol

The FR test was applied to 54 patients affected by type-2-diabetes mellitus: 17
diabetic non-neuropathic subjects (CTRL, 11 females and 6 males, 68.5 years old,
SD 3) and 37 diabetic neuropathic subjects (DN, 8 females and 29 males, 60 years
old, SD 11). Their clinical data and anthropometric measures are shown in Table
2.1.
Table 2.1. Clinical data and anthropometric measures of the analysed subjects.

<table>
<thead>
<tr>
<th></th>
<th>CTRL</th>
<th>DN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of subjects</td>
<td>17</td>
<td>37</td>
</tr>
<tr>
<td>Gender (M/F)</td>
<td>6/11</td>
<td>29/8</td>
</tr>
<tr>
<td>Age (years)</td>
<td>68.5±3</td>
<td>60±11</td>
</tr>
<tr>
<td>Body mass index (kg/m²)</td>
<td>28.7±4.2</td>
<td>28.9±4.8</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>162.5±10.5</td>
<td>167.5±9.5</td>
</tr>
<tr>
<td>Foot length (cm)</td>
<td>25.8±1.1</td>
<td>26.3±1.7</td>
</tr>
<tr>
<td>Duration of diabetes (years)</td>
<td>8.1±7.3</td>
<td>13.2±10.7</td>
</tr>
<tr>
<td>HbA1c (%)</td>
<td>7.3±0.9</td>
<td>7.6±1.0</td>
</tr>
</tbody>
</table>

CNTR = diabetic subjects; DN = diabetic neuropathic patients.
HbA1c, glycosylated hemoglobin.

All DN subjects suffered from symptomatic neuropathy and they were classified as symptomatic on the basis the Diabetic Neuropathy Symptom score, which was considered to be positive with a score of 1 or higher.

The study was approved by the Ethic Committee of the INRCA Hospital (process no. 124/2006) and all subjects gave their informed consent prior to testing. Exclusion criteria were: neuropathy other than that of diabetic origin or neurological disease, peripheral arterial disease or any medication potentially affecting peripheral nerve function.

The measurement protocol consisted in standing barefoot on a dynamometric platform (Kistler 9281 type) sampled at 100 Hz. To minimize the
subjects’ discomfort during the whole experimental session, the width of the base of support was maintained approximately equal to the pelvic width. The dominant arm was extended and kept perpendicular with respect to the trunk. The test consisted of moving the dominant arm as far forward as possible, maintaining the wrist above a yardstick which was positioned at shoulder height and parallel to the floor. The test had to be executed by the subjects at their maximum possible speed.

Kinematics was acquired by a 6-camera Elite optoelectronic system (BTS, sampling rate of 50 Hz). Twenty-six passive markers were placed on the various anatomical landmarks described in Table 2.2 and shown in Figure 2.3.

Table 2.2. Marker location.

<table>
<thead>
<tr>
<th>ACRONYM</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>MALL r,l</td>
<td>lateral malleolus right and left</td>
</tr>
<tr>
<td>MALL</td>
<td>midpoint between MALLr and MALLl</td>
</tr>
<tr>
<td>MET r,l</td>
<td>second metatarsal head right and left</td>
</tr>
<tr>
<td>MET</td>
<td>midpoint between METr and METl</td>
</tr>
<tr>
<td>HEL r,l</td>
<td>hell right and left</td>
</tr>
<tr>
<td>HEL</td>
<td>midpoint between HEElr and HEEl1</td>
</tr>
<tr>
<td>TC r,l</td>
<td>tibia lateral condyle right and left</td>
</tr>
<tr>
<td>TC</td>
<td>midpoint between TCr and TCI</td>
</tr>
<tr>
<td>FE r,l</td>
<td>femur lateral epicondyle right and left</td>
</tr>
<tr>
<td>FE</td>
<td>midpoint between FEr and FEI</td>
</tr>
<tr>
<td>GT r,l</td>
<td>greater trochanter right and left</td>
</tr>
<tr>
<td>GT</td>
<td>midpoint between GTr and GTl</td>
</tr>
<tr>
<td>IC r,l</td>
<td>iliac crests right and left</td>
</tr>
<tr>
<td>Term</td>
<td>Description</td>
</tr>
<tr>
<td>--------------------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>IC</td>
<td>midpoint between ICr and ICl</td>
</tr>
<tr>
<td>ASIS r,l</td>
<td>anterior superior iliac spinae right and left</td>
</tr>
<tr>
<td>ASIS</td>
<td>midpoint between ASISr and ASISl</td>
</tr>
<tr>
<td>PSIS r,l</td>
<td>posterior superior iliac spinae right and left</td>
</tr>
<tr>
<td>PSIS</td>
<td>midpoint between PSISr and PSISl</td>
</tr>
<tr>
<td>T12-L1r,l</td>
<td>spaces between the twelfth thoracic vertebra and the first lumbar vertebra right and left</td>
</tr>
<tr>
<td>T12-L1</td>
<td>midpoint between T12-L1r and T12-L1l</td>
</tr>
<tr>
<td>ACROM r,l</td>
<td>shoulder acromion right and left</td>
</tr>
<tr>
<td>ACROM</td>
<td>midpoint between ACROMr and ACROMr</td>
</tr>
<tr>
<td>TRAGO r,l</td>
<td>tragus right and left</td>
</tr>
<tr>
<td>TRAGO</td>
<td>midpoint between TRAGUSr and TRAGUSl</td>
</tr>
<tr>
<td>C7</td>
<td>seventh cervical vertebra</td>
</tr>
<tr>
<td>Wrist</td>
<td>dominant wrist</td>
</tr>
</tbody>
</table>

Figure 2.3. Marker location.
Data analysis

The FR distance was defined as the difference between the point of maximum forward extension of the wrist from its initial starting position and was normalised to the subject’s height (FR_H).

The FR-start instant was defined as the point in time immediately preceding the negative peak of COP excursion as shown in Figure 2.4, where the COG displacement is also shown.

Figure 2.4. COP (solid line) and COG (dashed line) displacement showing the FR-start and FR-end time instants.
This negative peak precedes the forward displacement of COP and is necessary to create a negative COP-COG displacement, thus initiating trunk flexion. The FR-end point was defined as the first time instant when the subject’s wrist speed reached zero, once the maximal speed had been attained. All parameters were computed relative to this time interval.

All kinematic data were filtered by a 4-th order low-pass Butterworth filter with a 5 Hz cut-off frequency.

Definition of parameters and motor strategies

Eighteen parameters were computed in total: 12 using markers placed on the anatomical landmarks (kinematic parameters) and 6 using COP or COG displacement data (stabilometric parameters). Their definition is given in Table 2.3. The COG was defined as the projection of the whole body centre of mass (COM) on the force platform; COM was estimated referring to a 14-segment model and to Winter’s anthropometric data [2.21]. The 14 segments considered were: legs (2), thighs (2), lower arms (2), upper arms (2), pelvis (1), trunk (4: the first segment being defined between shoulders and xiphoid process, the second between lower ribs and xiphoid process, the third between iliac crests and lower ribs, the fourth between iliac crests and ASIS), and head (1).
Table 2.3. Summary of the 18 computed parameters: acronyms and brief descriptions.

<table>
<thead>
<tr>
<th>ACRONYM</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FR_H</strong></td>
<td>FR distance normalised to the subject’s height.</td>
</tr>
<tr>
<td><strong>Flexion/extension parameters</strong></td>
<td></td>
</tr>
<tr>
<td>TRUNK FLEX 1</td>
<td>Maximum forward trunk flexion [2.15] (deg).</td>
</tr>
<tr>
<td>TRUNK FLEX 2</td>
<td>Range of trunk flexion defined by T12-L1 and IC markers (deg).</td>
</tr>
<tr>
<td>THIGH FLEX</td>
<td>Range of thigh flexion defined by GT and FE markers (deg).</td>
</tr>
<tr>
<td><strong>Rotation parameters</strong></td>
<td></td>
</tr>
<tr>
<td>TRUNK ROT 1</td>
<td>Thoracolumbar rotation [2.15] (deg).</td>
</tr>
<tr>
<td>LOWER ROT 1</td>
<td>Lower body rotation [2.15] (deg).</td>
</tr>
<tr>
<td>TRUNK ROT 2</td>
<td>Maximum thoracic rotation [2.15] (deg).</td>
</tr>
<tr>
<td>TRUNK ROT 3</td>
<td>Shoulder rotation [2.11] (deg).</td>
</tr>
<tr>
<td>LOWER ROT 2</td>
<td>Lumbar rotation [2.15] (deg).</td>
</tr>
<tr>
<td>TRUNK ROT 4</td>
<td>Maximum angle between the normal to the plane formed by PSIS and ACROMr and ACROMl and the axis that identifies the anterior-posterior direction (deg).</td>
</tr>
<tr>
<td>TRUNK ROT 5</td>
<td>Maximum angle between the normal to the plane formed by T12-L1 and PSISr and PSISl and the axis that identifies the anterior-posterior direction (deg).</td>
</tr>
<tr>
<td><strong>Lateral flexion</strong></td>
<td></td>
</tr>
<tr>
<td>LAT TRUNK FLEX</td>
<td>Lateral trunk flexion [2.15] (deg).</td>
</tr>
<tr>
<td><strong>STABILOMETRIC PARAMETERS</strong></td>
<td></td>
</tr>
<tr>
<td>RANGE COG AP</td>
<td>Maximum excursion of COG during reach in the sagittal plane (mm).</td>
</tr>
<tr>
<td>RANGE COG ML</td>
<td>Maximum excursion of COG during reach in the frontal plane (mm).</td>
</tr>
<tr>
<td>RANGE COP AP</td>
<td>Maximum excursion of COP during reach in the sagittal plane (mm).</td>
</tr>
</tbody>
</table>
RANGE COP ML  | Maximum excursion of COP during reach in the frontal plane (mm).
BOS FL       | Maximum sagittal plane displacement of COP normalised to the foot length [2.15] (%).
ALS COP      | Anterior limit of stability of COP: distance between anterior limit of BOS and the maximum anterior coordinate of COP (mm).

MatLab software was used to compute all the above parameters. Though some of them refer to literature [2.15], others were added. In particular, trunk rotation was computed in five different ways: three by angles defined in the transverse plane, and two by angles between segments defined in the 3D space.

The kinematic strategies used during the motor task were defined as follows [2.14]:

✓ “hip” strategy: characterised by a minimum of 20 deg of hip flexion and 5 deg of ankle plantarflexion;

✓ “other” strategy that included:
  • “mixed” strategy: hip flexion less than 20 deg and ankle plantarflexion greater than 5 deg;
  • “trunk rotation” strategy: trunk rotation in the transverse plane greater than 20 deg.

Statistical analysis

Principal Component Analysis (PCA) was used to select the most significant features among the set of kinematic and stabilometric parameters [2.22]. PCA was
applied both to CTRL and DN subjects, respectively. The minimum number of principal components (PCs) considered significant was determined using the Kaiser criterion. Varimax rotation was performed in order to try to obtain a group of homogeneous and significant variables correlated to a single PC [2.22]. For each component, significant parameters were considered from those exhibiting a score higher than 0.85, in absolute value.

Finally, Spearman’s rank correlation coefficient was used to test the association between FR_H and the other parameters and to verify which of these had the greater influence on reach distance. Correlation was assumed statistically significant at a level lower than 0.01.

The Mann-Whitney U test, with a significance level lower than 0.01, was used for two purposes: to check whether the use of different strategies influenced the distance reached, and to verify whether the parameter mean values in the two groups of subjects were different in a statistically significant way. SPSS software was used for the statistical analysis.

2.1.3 Results

Mean values and standard deviations of the computed parameters and the Mann-Whitney U test results are shown in Table 2.4. The mean execution time for
the FR-test was found to be 0.89 seconds (SD 0.26) and 0.84 seconds (SD 0.28) for CTRL and DN subjects, respectively.

Table 2.4. Mean value (mv) and standard deviation (SD) of computed parameters. No parameter results statistically significant at the Mann-Whitney-U test.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CTRL</th>
<th>DN</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR_H</td>
<td>0.14 (0.03)</td>
<td>0.14 (0.03)</td>
</tr>
<tr>
<td>TRUNK FLEX 1 (deg)</td>
<td>31.9 (13.2)</td>
<td>33.3 (12.5)</td>
</tr>
<tr>
<td>TRUNK FLEX 1 (deg)</td>
<td>31.8 (11.9)</td>
<td>32.1 (10.2)</td>
</tr>
<tr>
<td>THIGH FLEX (deg)</td>
<td>3.2 (1.5)</td>
<td>3.3 (1.1)</td>
</tr>
<tr>
<td>TRUNK ROT 1 (deg)</td>
<td>15.2 (5.6)</td>
<td>18.4 (9.3)</td>
</tr>
<tr>
<td>LOWER ROT 1 (deg)</td>
<td>8.3 (4.5)</td>
<td>9.7 (3.4)</td>
</tr>
<tr>
<td>TRUNK ROT 2 (deg)</td>
<td>9.7 (4.0)</td>
<td>9.0 (4.0)</td>
</tr>
<tr>
<td>LOWER ROT 2 (deg)</td>
<td>8.8 (2.6)</td>
<td>9.4 (3.6)</td>
</tr>
<tr>
<td>TRUNK ROT 3 (deg)</td>
<td>11.5 (5.4)</td>
<td>14.2 (7.9)</td>
</tr>
<tr>
<td>TRUNK ROT 4 (deg)</td>
<td>11.7 (6.1)</td>
<td>16.1 (7.9)</td>
</tr>
<tr>
<td>TRUNK ROT 5 (deg)</td>
<td>6.0 (3.1)</td>
<td>8.3 (4.2)</td>
</tr>
<tr>
<td>LAT TRUNK FLEX (deg)</td>
<td>8.6 (5.0)</td>
<td>6.0 (3.2)</td>
</tr>
<tr>
<td>RANGE AP COG (mm)</td>
<td>55.6 (16.9)</td>
<td>53.4 (21.0)</td>
</tr>
<tr>
<td>RANGE ML COG (mm)</td>
<td>21.3 (10.1)</td>
<td>22.0 (11.6)</td>
</tr>
<tr>
<td>RANGE AP COP (mm)</td>
<td>120.0 (46.5)</td>
<td>118.4 (25.2)</td>
</tr>
<tr>
<td>RANGE ML COP (mm)</td>
<td>41.2 (19.1)</td>
<td>48.5 (19.6)</td>
</tr>
<tr>
<td>BOS FL (%)</td>
<td>46.4 (17.9)</td>
<td>44.8 (10.2)</td>
</tr>
<tr>
<td>ALS COP (mm)</td>
<td>23.1 (9.8)</td>
<td>25.9 (7.8)</td>
</tr>
</tbody>
</table>

CTRL = diabetic subjects; DN, diabetic neuropathic subjects
For CTRL subjects, results indicate that the first 4 PCs account for 89% of the variance of the whole set of parameters. PC1 explains 40% of the entire data set variance while the other 3 PCs represent 49% of the total variance. The parameters that show the highest scores in the first four PCs are:

- for PC1: FR_H, TRUNK FLEX 1 and ALS COP;
- for PC2: LOWER ROT 1 and TRUNK ROT 5;
- for PC3: TRUNK ROT 1 and TRUNK ROT 2;
- for PC4: TRUNK ROT 3 and TRUNK ROT 4.

PC1 is mainly related to the trunk displacement in a forward direction during reach; the other 3 PCs describe body rotation in the transverse plane: in particular PC2 describes the rotation of the lower trunk, PC3 the rotation of the upper trunk, and PC4 shoulder rotation.

PCA results for DN subjects show that the first 4 PCs account for 84.6% of the total variation of the original parameters. PC1 explains 41.3% of the entire data set variance while the other 3 PCs represent 43.3% of the total variance. The parameters that show the highest scores in the first four PCs are:

- for PC1: TRUNK ROT 1, TRUNK ROT 2, LOWER ROT 1, TRUNK ROT 3, TRUNK ROT 4;
- for PC2: RANGE AP COP, BOS FL and ALS COP;
- for PC3: RANGE ML COG and RANGE ML COP;
- for PC4: LOWER ROT 1 and TRUNK ROT 5.

PC1, being different from the CTRL subjects, is mainly related to the body rotation in the transverse plane, both of the upper trunk and of the lower body. The score of the lower body rotation is noticeably high in PC4 too. PC2 describes COP displacement in the anterior-posterior direction during reach, while PC3 is related to body displacement in the medial-lateral direction.

Table 2.4 reports the mean value and the standard deviation of the computed parameters; this table shows that there are no statistically significant differences between corresponding parameter mean values of CTRL and DN groups.

Table 2.5 shows Spearman’s rank correlation coefficient between FR_H and all other parameters. In the CTRL group, FR_H is significantly correlated with parameters describing the body flexion in the sagittal plane, and with COG and COP parameters computed in the anterior-posterior direction. In DN subjects, the analysis shows high correlation mainly between the FR_H and trunk rotations, in particular with shoulder rotation in the transverse plane, and with parameters describing body displacement in the medial-lateral direction, such as COP and COG displacement.
Table 2.5. Spearman’s rank correlation coefficients between FR_H and all other parameters.

<table>
<thead>
<tr>
<th></th>
<th>CTRL</th>
<th>DN</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRUNK FLEX 1</td>
<td>.601</td>
<td>.356</td>
</tr>
<tr>
<td>TRUNK FLEX 1</td>
<td>.676**</td>
<td>.412</td>
</tr>
<tr>
<td>THIGH FLEX</td>
<td>.658**</td>
<td>.325</td>
</tr>
<tr>
<td>TRUNK ROT 1</td>
<td>.411</td>
<td>.201</td>
</tr>
<tr>
<td>LOWER ROT 1</td>
<td>.124</td>
<td>.278</td>
</tr>
<tr>
<td>TRUNK ROT 2</td>
<td>.350</td>
<td>.487**</td>
</tr>
<tr>
<td>LOWER ROT 2</td>
<td>.663**</td>
<td>.370</td>
</tr>
<tr>
<td>TRUNK ROT 3</td>
<td>.270</td>
<td>.549**</td>
</tr>
<tr>
<td>TRUNK ROT 4</td>
<td>.221</td>
<td>.519**</td>
</tr>
<tr>
<td>TRUNK ROT 5</td>
<td>.080</td>
<td>.338</td>
</tr>
<tr>
<td>LAT TRUNK FLEX</td>
<td>.259</td>
<td>.467**</td>
</tr>
<tr>
<td>RANGE AP COG</td>
<td>.754**</td>
<td>.585**</td>
</tr>
<tr>
<td>RANGE ML COG</td>
<td>.559</td>
<td>.503**</td>
</tr>
<tr>
<td>RANGE AP COP</td>
<td>.747**</td>
<td>.244</td>
</tr>
<tr>
<td>RANGE ML COP</td>
<td>.599</td>
<td>.454**</td>
</tr>
<tr>
<td>BOS FL</td>
<td>.748**</td>
<td>.315</td>
</tr>
<tr>
<td>ALS COP</td>
<td>-.751**</td>
<td>-.205</td>
</tr>
</tbody>
</table>

CTRL=diabetic subjects; DN=diabetic neuropathic subjects.

**p≤0.01

Table 2.6 summarises the kinematic strategies used by the two classes of subjects and shows the statistically significant differences in the FR and FR_H values between subjects that used “hip” strategy, “mixed” strategy or “trunk rotation” strategy in the two groups.
Table 2.6: Motor strategies used during FR test. Number of subjects (N), percentages, mean value (mv), standard deviation (SD) of FR_H, FR and reach time (RT) are reported. Mann-Whitney U test compares FR (and FR_H) values between “hip” and all the other strategies, within CTRL or DN groups, separately (p≤0.01).

* shows statistically significant differences between “hip” and “other” strategies;
† shows statistically significant differences between “hip” and “mixed” strategies;
+ shows statistically significant differences between “hip” and “trunk rotation” strategies.

<table>
<thead>
<tr>
<th>STRATEGY</th>
<th>CTRL</th>
<th>DN</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N (%)</td>
<td>FR (mm)</td>
</tr>
<tr>
<td></td>
<td>mv (SD)</td>
<td>mv (SD)</td>
</tr>
<tr>
<td>Hip</td>
<td>10  (58.8%)</td>
<td>266 (38)*†+</td>
</tr>
<tr>
<td>Other</td>
<td>7   (41.2%)</td>
<td>198 (42) *</td>
</tr>
<tr>
<td>Mixed</td>
<td>6   (85.7%)</td>
<td>201 (44) †</td>
</tr>
<tr>
<td>Trunk rotation</td>
<td>1   (14.3%)</td>
<td>177 +</td>
</tr>
</tbody>
</table>

CTRL=diabetic subjects; DN=diabetic neuropathic subjects.
2.1.4 Discussion

This study describes the main parameters that characterise the FR test performed in diabetic and diabetic neuropathic subjects. Results show the presence of different movement strategies used by these two classes of patients.

Previous studies based on the kinematic analysis of the FR test were only performed on young adults [2.15], healthy elders [2.12, 2.15] or individuals with vestibular dysfunction [2.14] but not diabetic neuropathic subjects.

In this work it was decided to make reference to FR_H, (i.e. the FR distance normalised with respect to the subject’s height) and not simply to the classic FR measure, in order to avoid the influence that the subject’s height can have on FR measure [1.14]. Table 2.4 shows no statistically significant difference between parameter mean values relative to CTRL and DN classes, respectively. This finding confirms that, at first glance, it is not possible to differentiate between CTRL and DN subjects on the basis of a particular kinematic or stabilometric parameter, this is particularly true for the FR or FR_H values. It is therefore necessary to perform a much closer data analysis in order to determine the FR execution modality between the two groups.

Parameters already documented in literature [2.15] have been computed to describe movement kinematics. Besides, different parameters have been used to
describe trunk rotation. In this way, it was possible to consider separately the 
contribution of the different trunk segments on the FR performed: the whole trunk 
(between ACROM and PSIS), the shoulders, the thorax (between ACROM and 
T12-L1) and the lumbar segment (between T12-L1 and PSIS). This method aided 
in the understanding of which body part was more involved in the rotations that 
characterise the execution of the motor task. In the DN group, the correlation 
analysis shows that FR is significantly correlated with the rotation of the upper and 
of the lower trunk, whereas the rotation of the trunk, considered as a whole 
segment, was not found to be correlated with FR in a statistically significant 
manner.

The analysis of stabilometric parameters, especially the COP and COG 
displacement in anterior-posterior and medial-lateral directions, shows as COP 
excursions in both directions are twice the value of the COG in the two categories 
of patients. This finding underlines that, in both cases, there is an efficient control 
action that minimises the COG displacement, thus dynamically stabilising the 
body. In the control group, a statistically significant correlation between FR_H and 
anterior-posterior displacement of COP and COG was observed. Conversely, in the 
DN group, results show a significant correlation of FR_H with the medial-lateral 
excursion of COP and COG. This means that diabetic patients without neuropathy 
and diabetic neuropathic subjects tend to move their body in different planes during
the task. In particular, the CTRL subjects tend to move mainly in the sagittal plane, while the DN patients also exhibit a significant medial-lateral displacement.

In the CTRL group, the values of the kinematic parameters are in accordance with those reported in a previous study conducted on the elderly [2.11]. However, the mean FR distance (232 mm, SD 55) was found to be lower than the mean FR value obtained from age-matched healthy elderly subjects as reported in [1.14, 2.3, 2.11, 2.18] that turns out to be not less than 300 mm. A possible explanation of this finding could be related to the modality of test execution. In fact, in the present work the subjects had to perform the task at their maximal speed, while in the aforementioned studies, each subject performed the FR test at his/her preferred speed, which could possibly have been lower with respect to the average maximal velocity adopted here.

Principal component analysis allowed to understand which parameters are more suitable to describe the modalities of the reaching task in the two categories of diabetic subjects. The feature selection, independently applied to the parameters obtained in the two groups of subjects, gave different results. The first principal component (PC1), is the most relevant because it explains more than 40% of the entire data set variance. PC1 also shows that for the CTRL subjects the most important parameters are those related to trunk flexion in the sagittal plane. On the contrary, for DN subjects, the main features are related to upper and lower body
rotations. Moreover, the other principal components show that trunk displacement in the medial-lateral direction is also significant in the DN group. So, results reveal that diabetic non-neuropathic and neuropathic subjects use different modalities to perform the FR test. This finding is further confirmed by correlation analysis. In fact, in the control group, FR_H is significantly correlated only with body displacement in the sagittal plane; but in the diabetic neuropathic group, there is a significant correlation between FR_H and parameters describing trunk rotation and body movement in the frontal plane. The two statistical methods (PCA and correlation analysis) lead to the same conclusion, namely that FR_H is dependent upon different sets of parameters according to the type of subjects analysed. These results strengthen the idea of the existence of different execution modalities of the FR test: CTRL subjects perform the task by pushing the trunk forward in the sagittal plane, whereas a consistent part of DN subjects combine this movement with trunk rotation in association with its displacement in the medial-lateral direction. Therefore, it can be stated that the trunk rotation is a feature that mainly characterises the FR test performed by diabetic neuropathic subjects. For the CTRL group, the results agree with those reported in [2.11] for the elderly in which trunk rotation does not show significant association with FR. The above results, and the findings of Wernick-Robinson et al. [2.14], allow the subdivision of the analysed subjects into two main categories, according to the motor strategies utilised. The
“hip” strategy, as expected, is the most utilised by all the subjects. The “other” strategy has been subdivided into two other subcategories: namely the “mixed” strategy, where both ankle dorsiflexion and hip flexion are reduced with respect to the “hip” strategy; the “trunk rotation” is the second subcategory that indicates a significant shoulder rotation in the horizontal plane.

As shown in Table 2.6, among the CTRL subjects, 58.8% used “hip” strategy and the remaining 41.2% used “other” strategy. Concerning the latter, 85.7% used “mixed” strategy and only 14.3% the “trunk rotation” strategy. Similarly, in DN patients, 56.7% employ “hip” strategy and 43.3% the “other” strategy but, within in this last group, 62.5% used “mixed” strategy and 37.5% rotated the trunk in order to reach forward.

As shown in Table 2.6, the DN group, does not show statistically significant differences in the FR_H values between subjects that used “hip” strategy, “mixed” strategy or “trunk rotation” strategy. Instead, in the CTRL group, the subjects that used “hip” strategy performed a greater FR than subjects that employed “other” strategies. This can be explained by the fact that diabetic subjects are not aware of their functional limitations that, if exist, are at a subclinical level. On the contrary, DN subjects are well aware of their sensory/motor deficits and activate compensatory strategies to perform a maximal motor task such as FR. So different FR/FR_H values are produced by CTRL subjects according to the preferred
strategy. Instead, DN subjects, aware of their limitations, seem to compensate their deficiencies with different motor strategies to reach as far forward as possible.

To summarise, the percentages of subjects which used “hip” or “other” strategies are similar between the CTRL and DN groups. However, within the “other” strategy group, the percentage of DN subjects that use a “trunk rotation” strategy is much higher than for CTRL ones (37.5% DN vs 14.3% CTRL).

This result highlights how similar FR_H values can be obtained by different movement strategies [2.16] and this is particularly true for DN subjects. While for diabetic non-neuropathic subjects, FR is mainly performed by trunk flexion in the sagittal plane, for diabetic neuropathic patients, FR is also significantly accomplished by trunk rotation in the horizontal plane. A possible explanation of this fact may be the fear of falling that most DN subjects experience, due to the alteration of the proprioceptive afferents. This factor could make them implement a different motor strategy in order to reach forward, by using lateral and torsional movements of the trunk. Another possible explanation could be the weakness of the posterior leg muscle group in DN subjects that tends to reduce the forward trunk displacement.

In conclusion, as reported in literature [2.14, 2.15, 2.23], the kinematic analysis used to assess the motor strategy adopted during the FR test provides different information on how balance control is performed. When reaching forward with one
arm although a great part of movement occurs in the sagittal plane, rotational movements in the transverse and coronal planes also occur and cannot be disregarded.

The results of this study show that the two classes of diabetic subjects adopt different movement strategies during forward reaching. The evaluation of the motor strategy, in addition to the measurement of the forward displacement of the arm, might be useful in the early detection of the subjects at risk of postural instability. Thus the different strategies adopted in the DN group could be due to compensatory mechanisms that allow the maintenance of the dynamic equilibrium while performing a destabilizing task as FR.
2.2 SURFACE ELECTROMYOGRAPHIC ANALYSIS DURING THE FUNCTIONAL REACH TEST IN DIABETIC SUBJECTS

In the light of the above results, it was thought interesting to analyse the muscle behaviour during the Functional Reach Test in the same categories of subjects, i.e. neuropathic and non-neuropathic diabetic patients.

2.2.1 Introduction

Essentials of muscle physiology

In order to understand how skeletal muscles work to produce segment body movement, it is necessary to understand what happens at a microscopic level. Simplified schematic diagrams of the central motor system and the concept of the motor unit (MU) are presented in Figure 2.5 [2.24].

Figure 2.5. Schematic representation of basic motor control mechanism and of the motor unit and its components [2.24].
The central nervous system is organised in a hierarchical fashion. Motor programming takes place in the premotor cortex, the supplementary motor area and other associated areas of the cortex. Inputs from these areas, from the cerebellum and from the basal ganglia converge to the primary motor cortex and excite or inhibit the various neurons of the primary motor cortex. The outputs from the primary motor cortex have a powerful influence on interneurons and motoneurons of the brain stem and of the spinal cord. There exists a link between the corticospinal tract and alpha-motoneurons (α-motoneurons), providing direct cortical control of muscle activity (Figure 2.5) [2.24].

A MU consist of an α-motoneuron and of the muscle fibers it innervates. In humans a classification of motor units based on their physiological properties is difficult to achieve. Therefore, it is generally accepted that muscle fiber can be broken down into two main types: slow twitch (Type I) muscle fibers and fast twitch (Type II) muscle fibers. Fast twitch fibers can be further categorized into Type IIa and Type IIb fibers. Muscles can be classified according to the muscular fibers that compose them: tonic muscles contain mostly slow-twitch muscle fibres, and act predominantly to sustain body posture in the gravity field; phasic muscles contain mostly fast-twitch muscle fibres, and are therefore more suited to movement [2.25].
Background

“Electromyography is the study of muscle function through the inquiry of the electrical signal the muscle emanates” [2.26].

The purpose of this second part of the thesis is the identification of movement patterns performed during the Functional Reach Test using surface electromyography (SEMG).

In literature, only forward and backward movements of the trunk in older subjects have been analysed by electromyography [2.27-2.32]; muscle activity is influenced by a number of reaching task parameters, such as reaching speed, reaching direction and inertial load. Changes in these task parameters affect the magnitude and direction of the forces that perturb balance. As the direction and speed of reaching movements are varied, the muscle activity also changes. With different reaching distances, the challenge to standing balance changes, too. As reaching distance is increased, displacement of the whole body centre of mass is increased [2.28-2.29]. These studies affirm that upper trunk bending in humans is accompanied by lower segment movements in the opposite direction. In fact the execution of voluntary movement evokes both inertial and gravitational forces acting upon the segment chain. This phenomenon, called “axial synergy”, is aimed to prevent large anterior-posterior shift of the centre of gravity thus helping in maintain equilibrium during the movement [2.31]. It was found that upper trunk
movements are accompanied by movements of hip and knees in the opposite
direction, resulting in a slight displacement of the centre of gravity projection on
the ground. In fast movements, all the body segments are displaced at the same
time, whereas in slow movements, the onset of body segment displacement takes
place sequentially in a cranio-caudal direction: soleus inhibition, tibialis anterior
activation and vastus medialis activation in close temporal correlation, in most
cases preceding the prime mover (rectus abdominis) activation [2.28]. A great deal
of experimental evidence during, for example, arm and leg raising, forward and
backward bending, or rising onto tiptoes has, outlined postural activity preceding
movement onset. This activity describes the reflex which prevent the body from
falling. These reflexes activate the muscle before the reaction to the postural
changes and they can be also defined as “anticipatory postural adjustment” [2.30].
In fact, in most cases, the set of muscles responsible for those postural changes and
for movement initiation is activated in advance with respect to the prime movers,
indicating that a feedforward type of neural control is involved [2.27, 2.28].
Several experimental results have shown that the initiation of a large repertoire of
forward oriented movements without modifications of base of support or target
distance were accompanied by the soleus inhibition and tibialis anterior activation
[2.31]. In [2.29] it was suggested that all target distances are associated with
anticipatory muscle activity, which for more distant targets, appears remarkable
earlier. In particular, the onset of tibialis anterior, vastus lateral and erector spinae showed the clearest and most consistent patterns of change in response to varying target distance [2.29]. It is believed that identifying consistent, distance-dependent changes in anticipatory activity of leg, thigh, and trunk muscles in healthy adults may allow detection of subtle postural control changes in individuals with balance deficits. In other studies [2.27, 2.32] it was noticed that during trunk flexion movements of different amplitudes, the cessation of activity in erector spinae always preceded the onset of activity in rectus abdominis. Time for onset of activity in prime movers was invariant over the whole movement range. Activity in tibialis anterior appeared late (after the start of trunk flexion) for small movements and, for larger movements, its activation occurs before in proportion to the movement increase, causing a change in the order of activation from proximal to distal (rectus abdominis first) to distal to proximal (tibialis anterior first).

This second part of this study is aimed at investigating the activation patterns of muscles involved in the Functional Reach Test in diabetic non-neuropathic and neuropathic subjects and at verifying the presence of “anticipatory postural adjustments”.
2.2.2 Materials and Methods

Subjects and experimental protocol

The FR test was applied to 10 diabetic patients affected by type-2-diabetes mellitus: 5 diabetic non-neuropathic subjects (CTRL, 2 females and 3 males, 65.2 years old, SD 20) and 5 diabetic neuropathic subjects (DN, 1 females and 4 males, 65.6 years old, SD 10). Their clinical data and anthropometric measures are shown in Table 2.7.

Table 2.7. Clinical data and anthropometric measures of the analysed subjects.

<table>
<thead>
<tr>
<th></th>
<th>CTRL</th>
<th>DN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of subjects</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Gender (M/F)</td>
<td>3/2</td>
<td>4/1</td>
</tr>
<tr>
<td>Age (years)</td>
<td>65.2±20</td>
<td>65.2±10</td>
</tr>
<tr>
<td>Body mass index (kg/m²)</td>
<td>30.2±2.9</td>
<td>28.79±3.7</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>163±12</td>
<td>169±4.6</td>
</tr>
<tr>
<td>Foot length (cm)</td>
<td>25.3±1.5</td>
<td>26.1±0.7</td>
</tr>
<tr>
<td>Duration of diabetes (years)</td>
<td>7.3±4.2</td>
<td>14.1±8.7</td>
</tr>
<tr>
<td>HbA1c (%)</td>
<td>7.1±0.8</td>
<td>7.4±1.2</td>
</tr>
</tbody>
</table>

CTRL = diabetic subjects; DN = diabetic neuropathic patients.
HbA1c, glycosylated hemoglobin.

All DN subjects suffered from symptomatic neuropathy and they were classified as symptomatic on the basis the Diabetic Neuropathy Symptom score, which was considered to be positive with a score of 1 or higher.
The protocol is the same as that shown in first part of this thesis but with the addition of 7 EMG active probes for surface electromyography placed unilaterally (dominant side) on the following muscles: Sternocleidomastoideus (Scm), Rectus Abdominis (RAbd), Erectores Spinae at L4 level (L4), Rectus Femoris (RF), Hamstrings (Ham), Tibialis Anterior (TA) and Soleus (Sol) as shown in Figure 2.6. All EMG electrodes were positioned over the most prominent part of the respective muscle belly.
In this case, kinematic data were acquired using a 6-camera optoelectronic system (BTS SMART D, sample rate 120 Hz), dynamometric data were acquired using a dynamometric platform (Kistler, sample rate 480 Hz) and muscles activity was recorded using wireless 8-channel surface electromyography (BTS FREE EMG 300, sample rate 1000 Hz). The FR test was repeated three times by each subject.

Data analysis

The analysis of kinematic and dynamic data, was performed as described in the first part of this thesis. The EMG signals were full-wave rectified and band-pass filtered (35-500 Hz). The EMG analysis was conducted considering the root mean square (RMS) value of the SEMG signal because during voluntary contractions, the RMS value seems to be more appropriate [2.26]; in fact it represents the signal power and thus has a clear physical meaning; on the contrary, other EMG processing methods that make reference to the average rectified value of the SEMG signal, i.e. at the area under the rectified EMG trace, do not have a specific physical meaning. To detect muscles’ ON-OFF the double-threshold algorithm described in [2.33] was implemented. The application of this algorithm requires an estimate of the noise level superimposed at the SEMG signal; consequently it is necessary to record for each channel and for a few seconds a signal with muscle in
non-contracted and isometric conditions. For this reason, the data acquisition starts 5 seconds before the voice signal is given to the subject to start the FR task. A simple approach to evaluate the value of the threshold value is to calculate this value at two standard deviations from the mean value. In this study, the threshold has not been computed over the entire noise period (5 seconds) but, within this period, a sliding window of 50 milliseconds has been defined. Within each sliding window, a threshold value has been computed and, between all the threshold values obtained, has been chosen the one with lowest value. The time instants at which the SEMG signal exceeds, or remains below the threshold for at least 50 ms may be considered, respectively, as the ON or the OFF time instants of muscle activity.

For each subject the ON–OFF time instants relative to each muscle were averaged over the three trials performed by each subject.

2.2.3 Results

The mean value of execution time and of FR_H for the FR-test were found to be, for CTRL subjects, 0.80 seconds (SD 0.09) and 0.13 (SD 0.02) respectively, while for the DN group 0.73 seconds (SD 0.21) and 0.11 (SD 0.03) respectively.
Table 2.8 and Table 2.9 show mean values and standard deviation of hip flexion, ankle plantarflexion and trunk rotation with the strategy used by CTRL and DN groups, respectively.

Table 2.8. Mean value (mv) and standard deviation (SD) of hip flexion, ankle plantarflexion and trunk rotation with the strategy of CTRL groups.

<table>
<thead>
<tr>
<th>STRATEGY</th>
<th>MV (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTRL</td>
<td></td>
</tr>
<tr>
<td>Subject A</td>
<td></td>
</tr>
<tr>
<td>Subject B</td>
<td></td>
</tr>
<tr>
<td>Subject C</td>
<td></td>
</tr>
<tr>
<td>Subject D</td>
<td></td>
</tr>
<tr>
<td>Subject E</td>
<td></td>
</tr>
<tr>
<td>Hip flexion [deg]</td>
<td>18.2 (1.1)</td>
</tr>
<tr>
<td>Ankle plantarflexion [deg]</td>
<td>10.0 (0.3)</td>
</tr>
<tr>
<td>Trunk rotation [deg]</td>
<td>15.1 (3.2)</td>
</tr>
<tr>
<td>Strategy</td>
<td>Mixed</td>
</tr>
</tbody>
</table>

Table 2.9. Mean value (mv) and standard deviation (SD) of hip flexion, ankle plantarflexion and trunk rotation with the strategy of DN groups.

<table>
<thead>
<tr>
<th>STRATEGY</th>
<th>MV (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DN</td>
<td></td>
</tr>
<tr>
<td>Subject A</td>
<td></td>
</tr>
<tr>
<td>Subject B</td>
<td></td>
</tr>
<tr>
<td>Subject C</td>
<td></td>
</tr>
<tr>
<td>Subject D</td>
<td></td>
</tr>
<tr>
<td>Subject E</td>
<td></td>
</tr>
<tr>
<td>Hip flexion [deg]</td>
<td>17.5 (3.2)</td>
</tr>
<tr>
<td>Ankle plantarflexion [deg]</td>
<td>14.2 (0.3)</td>
</tr>
<tr>
<td>Trunk rotation [deg]</td>
<td>11.7 (1.5)</td>
</tr>
<tr>
<td>Strategy</td>
<td>Mixed</td>
</tr>
</tbody>
</table>

Mean values and standard deviations of the instant of muscle activations in CTRL and DN subjects expressed in percentage of FR task duration are shown in Table 2.10 and Table 2.11, respectively.
Table 2.10. Mean value (mv) and standard deviation (SD) of the instant of muscle activations in CTRL subjects expressed in percentage of FR task duration.

<table>
<thead>
<tr>
<th>CTRL</th>
<th>Instant of Muscle Activation [% of FR period]</th>
<th>mv (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Subject A</td>
<td>Subject B</td>
</tr>
<tr>
<td>Scm</td>
<td>20.8 (33.8)</td>
<td>3.2 (11.8)</td>
</tr>
<tr>
<td>L4</td>
<td>29.7 (5.7)</td>
<td>19.8 (2.9)</td>
</tr>
<tr>
<td>RAbd</td>
<td>-3.3 (3.1)</td>
<td>-9.2 (2.2)</td>
</tr>
<tr>
<td>RF</td>
<td>-16.3 (2.4)</td>
<td>-24.9 (5.8)</td>
</tr>
<tr>
<td>Ham</td>
<td>22.1 (11.4)</td>
<td>-7.2 (16.0)</td>
</tr>
<tr>
<td>TA</td>
<td>-20.5 (0.4)</td>
<td>-26.8 (5.2)</td>
</tr>
<tr>
<td>Sol</td>
<td>25.7 (7.7)</td>
<td>11.9 (8.5)</td>
</tr>
</tbody>
</table>

Table 2.11. Mean value (mv) and standard deviation (SD) of the instant of muscle activations in DN subjects expressed in percentage of FR task duration.

<table>
<thead>
<tr>
<th>DN</th>
<th>Instant of Muscle Activation [% of FR period]</th>
<th>mv (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Subject A</td>
<td>Subject B</td>
</tr>
<tr>
<td>Scm</td>
<td>18.8 (5.1)</td>
<td>-10.4 (6.9)</td>
</tr>
<tr>
<td>L4</td>
<td>37.4 (0.5)</td>
<td>12.7 (7.3)</td>
</tr>
<tr>
<td>RAbd</td>
<td>38.5 (11.2)</td>
<td>7.7 (27.3)</td>
</tr>
<tr>
<td>RF</td>
<td>-</td>
<td>-24.8 (5.9)</td>
</tr>
<tr>
<td>Ham</td>
<td>24.3 (34.4)</td>
<td>-5.0 (20.3)</td>
</tr>
<tr>
<td>TA</td>
<td>1.2 (9.3)</td>
<td>-28.9 (4.2)</td>
</tr>
<tr>
<td>Sol</td>
<td>21.1 (7.9)</td>
<td>7.4 (9.6)</td>
</tr>
</tbody>
</table>
Figure 2.7 shows the muscle activations of the diabetic non-neuropathic subjects. In all CTRL subjects, the anterior muscles of the trunk (Scm, RAbd, RF, TA) are active before the beginning of the movement. In each subject the first motor is TA that contracts at -25% of the movement, and the last muscle to be active among these ones is the Scm. According to the number and mode of activations of this muscle, the subjects can be divided into two groups: in the first group (subjects A and D), the TA is active before the start and turns off immediately after it; in the second group (subjects B, C and E), the muscle presents a double activation (before the start and near the end of the movement) or is characterised by a single prolonged activation for the whole duration of the motor task. There exists activation synchronism of the posterior muscles (L4, Ham and Sol) approximately at 20% of the FR.

Figure 2.8 shows the muscle activations of the diabetic neuropathic subjects. In four subjects out of five (subjects B, C, D, E), TA is the first motor, and its activation occurs at around -30% of the movement. It shows a double or a prolonged activation. In all DN patients, the posterior muscles (except the Ham that is activated near the start) show a synchronous activation after the start.
Figure 2.7. Activations interval of the muscles considered in the CTRL subjects analysed (A-E). The diagram shows the mean value and the standard deviation of the three repeated tests. Time axis is normalized between -50% and 100%. The 0% is the start time instant (red dashed line); the 100% is the end time instant (blue dashed line).
Figure 2.8. Activations interval of the muscles considered in the DN subjects analysed (A-E). The diagram shows the mean value and the standard deviation of the three repeated test. Time axis is normalized between -50% and 100%. The 0% is the start time instant (red dashed line); the 100% is the end time instant (blue dashed line).
Figures 2.9 and 2.10 show the instant of the muscles activation in the CTRL and DN subjects.

Figure 2.9. Instants of muscle activation in the CTRL subjects.

Figure 2.10. Instants of muscle activation in the DN subjects.
2.2.4 Discussion

This study describes the activations of several muscles during the FR test in non-neuropathic and neuropathic diabetic subjects. Results show analogies and differences in the timing of muscle activations between these two categories of patients.

It is worth mentioning a high repeatability of EMG activation sequence within each subject; moreover the analysis of EMG patterns among subjects in each categories analysed reveals analogies but also differences in the sequence of EMG activation.

In CTRL subjects, the anterior muscles have a precise activation order from the lower part of the body to the top (TA, RF, RAbd, Scm) following a caudo-cranial order. Therefore, a synergism of the anterior muscle chain exists: this synergism allows the imbalance of the body. All these muscles begin their action before the start (Table 2.10); the last muscle to be activated is Scm that, for some subject A, B and D, is ON after the start (Figure 2.7). This muscle has several functions, but it is primarily a flexor. When the muscle works asymmetrically, such as during the FR, it acts as an extensor that must keep the head parallel to the floor and promotes the trunk progression forward. For this reason, the Scm begins to contract after the other back muscle, so as to maintain a stable position of the head and to push
forward the trunk. In correspondence with 20% of the movement, the posterior muscles begin their activity, as shown in Figure 2.9 and in Table 2.10. There is a synergistic tonic action of Sol and Ham followed by L4 activation. In fact, the back muscles act mainly as tonic muscles that oppose to the movement, preventing falls.

In DN subjects, except for a subject (subject A), the TA is activated earlier than its activation in non-neuropathic subjects. The diabetic neuropathic subjects have a problem of proprioception which manifests as a delay in the recruitment of the motor units and as a reduced nervous conduction velocity; consequently it is probable that DN subjects put into action an anticipatory recruitment to compensate for the delay and to adjust the movement timing. This mechanism describes the early muscle predisposition to perform the movement.

In all CTRL and DN subjects, the TA can be recognized as the first muscle to contract and its action can be attributed to the anticipatory muscular activity necessary to initiate the movement creating useful conditions for forward displacement of the body. Its activation, preceding the movement starts, is necessary to move the COP backward and to give rise to the ankle dorsi-flexor moment, thus unbalancing the body forward. RF is activated before or close to the movement start: in fact it works as a hip flexor, and consequently it contributes to bend the trunk forward and it acts when acceleration is required, namely when the movement has to begin.
When TA is inhibited, there is a synergistic tonic action of L4, Ham and Sol that opposes to the forward body fall (Figure 2.7 and Figure 2.8). In this case Sol, that is a TA antagonist, acts in a tonic manner to plantar-flex ankle joint and Ham has a braking function to prevent hyperextension of the knee.

In CTRL subjects, two different types of muscle activations have been found: in the first case, the TA is active before the start and turns off immediately after it; in the second case the muscle either has a double activation (before the start and near the end of the movement), or a single prolonged activation for the whole duration of the motor task. On the contrary, in the DN subjects, the TA pattern is unique and has a pattern similar to the CTRL second case. These two muscular patterns identify two different motor strategies used by the subjects. The first modality, characterised by a single activation of the TA, is associated to a mixed strategy (as shown in Table 2.8) characterized by a reduced flexion of the hip. In this case, the body is moved as a single segment, and the TA has only a phasic function, responsible for the start of the movement. The second modality, characterised by a double activation of TA (or by a prolonged activation of this muscle), is associated to a hip strategy (Table 2.8) with a greater hip flexion. During the execution of this strategy, two phases can be identified: during the first one, the pelvis is pushed backward and the TA has a tonic action; during the second one, the trunk is pushed forward and the TA has a phasic action. It is interesting to note the behaviour of
two CTRL subjects (B and C) that show a greater ankle plantarflexion than the other subjects. These values indicate a noticeable pelvis displacement backward before pushing the trunk forward. All DN subjects, expect one, chose this second strategy probably because they have a situation of greater instability and insecurity; consequently they tend to use a strategy in which they may exert more control, thus breaking the reaching movement in two different parts. In this group, subjects B shows a hip flexion of 44 deg, greater than that of the other subjects, accompanied by an increased activity of tonic muscles RF and Ham (Figure 2.8) which must prevent the forward fall of the body.

Results have shown that electromyography can provide useful information about how the FR test is performed. In particular, results suggest that the anticipatory postural adjustment patterns exerted during the FR task do not only serve to control the final body posture or to counterbalance the forthcoming movements perturbations, but are responsible of creating the proper centre of pressure displacement within the base of support necessary to create initial destabilizing moments and thus to promote the movement of the body forward, as shown in Figure 2.4. Therefore, the muscle activity before the start of the movement has a primary role in the movement performance and also in the equilibrium control. In addition, the difference in the timing of TA activation
between CTRL and DN subjects may be a key element to identify the presence of neuropathy in the diabetic subjects.

At the end of the movement, the tonic action of the posterior muscles is present. This muscular activation is common to both groups of subjects (Figure 2.7 and Figure 2.8) and it is necessary to prevent the forward fall of the body. This action confirms the important role of these muscles that, though they do not participate in the movement generation, limit the excessive forward unbalance of the body.
Chapter 3.

Concluding Remarks

A description of kinematic, dynamic and electromyographic features that characterise the Functional Reach Test in non-neuropathic and neuropathic diabetic subjects has been proposed.

The results of this study show that the two groups of all subjects tend to move their body in different planes during the task. In particular, the CTRL subjects tend to move mainly in the sagittal plane, while the DN patients also exhibit a significant medial-lateral displacement. In fact, the two groups adopt different movement strategies during forward reaching: for diabetic non-neuropathic subjects, FR is mainly performed by trunk flexion in the sagittal plane while, for diabetic neuropathic patients, FR is also significantly accomplished by trunk rotation in the horizontal plane. Thus the different strategies adopted in the diabetic neuropathic group could be due to compensatory mechanisms that allow the maintenance of the dynamic equilibrium while performing a destabilizing task as Functional Reach. The EMG activations in neuropathic and non-neuropathic diabetic subjects confirmed that, during the FR task, the prime motor is the TA. In all subjects, this muscle can be recognized as the first muscle to contract and its
action can be attributed to the anticipatory muscular activity necessary to initiate
the movement creating useful conditions for forward displacement of the body. Its
activation before the movement starts is necessary to move the COP backward and
to give rise to the ankle dorsi-flexor moment able to unbalance the body forward.
The difference is in the timing of this muscle activation: in fact, in diabetic
neuropathic patients, the tibialis anterior is activated earlier than its activation in
non-neuropathic subjects. However, in all subjects, when TA is inhibited, there is a
synergistic tonic action of L4, Ham and Sol that opposes to the forward body fall.
In this case Sol, that is a TA antagonist, acts in a tonic manner to plantar-flex ankle
joint.
The evaluation of the motor strategy and the electromyographic analysis of several
trunk, thigh and shank muscles, in addition to the measurement of the forward
displacement of the arm, might be useful for the early detection of the subjects at
risk of postural instability.
References


