POLITECNICO DI MILANO

Scuola di Ingegneria Industriale e dell'Informazione

Corso di Laurea Magistrale in Ingegneria Biomedica
(indirizzo clinico BCI)

Multi-sensor actigraphic long-lasting monitoring in healthy subjects

Relatore: Prof. Carlo Frigo

Correlatore: Ing. Marco Rabuffetti

Tesi di Laurea Magistrale di:

Alex Fugazza

Mtr. 816612

Anno Accademico 2014/2015

Summary

Abstract

The last twenty years have seen a significant development and diffusion of wearable and portable devices in healthcare and rehabilitation. Their diffusion is linked to the will to improve the methods used to assess human movement and performance circumventing some limits of the classical motion analysis laboratory investigations. Even if the laboratory setting, with its highly reliable and accurate instruments (e.g., optoelectronic system, force-platforms etc.), is still considered an essential tool for an effective assessment of human movement in clinic and research, today there is a broad consensus in recognizing some of its limits. In particular, has been highlighted also by WHO (World Health Organization), the importance, during motor analysis, of distinguish *motor capacity* and *motor performance*, complementary elements in an accurate analysis of impaired and health people. *Motor capacity* is namely the motor ability a subject can express during specific motor exercises and tasks performed in a controlled environment, under the supervision of professional staff, just as in a laboratory; so that motor capacity assessment includes gait analysis, reaching test or other similar standardized motor investigations, often asking for close-to-the-limit behaviors. On the other side, *motor performance* is defined as the motor potential a subject expresses during every day life activities in a free-living environment: everything that one can not observe inside a laboratory. Considering motor impaired people, assessing their motor performance means focusing on their daily issues and difficulties: the laboratory investigation is surely rich and satisfactory in terms of quality and amount of extracted data, but this does not mean that it is able to draw a complete picture of a motor situation; a classical example is the disabled subject who strives to complete a laboratory task providing certain results, but, during everyday life, faces obstacles in similar activities because he is not asked to reach targets and push his limits. It is exactly in this context that portable and wearable devices try to establish themselves as complementary tools to the classical motion analysis investigation, because able to partially free surveys from labs, toward what is called an *ecologic environment*.

Portable and wearable devices are many and different, but a certain attention have been paid to actigraphy. Actigraphs are wearable devices able to measure movement thanks to the use of accelerometer-based technology and do this also for long periods (e.g., 24 hours): long-lasting monitoring are not feasible in laboratory, in which surveys lasts at most minutes, since they are based on specific identical exercises repeated a certain number of time (e.g., a walk on a gangway). Over the decades actigraphs have been used in different contexts (e.g., also sleep medicine), but today it is traceable a main interest in monitoring neurological pathologies' consequences (e.g., impairments derived from stroke, Parkinson's disease etc.) or the physical daily activity to assess the perceived health of young, middle-aged and elder people; given the impact of neurological disease is possible to observe that the 62.9% of researches concerning these pathologies and involving wearable device is oriented on rehabilitation [28] .

The study proposed in this thesis aims to draw a preliminary picture of health subjects using motor indexes specifically designed at the purpose and a set of four devices (*GENEActiv Original*) based on a MEMS - triaxial accelerometer during a 24h monitoring. The monitoring configuration provides the presence of two devices on the upper limbs at the level of the wrists, a third sensor located on the pelvis, strapped to an elastic waist-belt at the level of the sacrum and a last fourth sensor on one of the lower limbs at the level of the ankle (the lower limb chosen depends on the subject's handedness). This setup aims to provide a global picture of motor activity during the day.

In particular we defined two different kind of indexes:

- Motor Activity index for epoch MA_e (declined also in overall MA_{24h} values) obtained from a single sensor.
- Activity Ratio AR_{24h} indexes obtained from coupled sensors.

The Motor Activity index is a robust epoch-related variable able to summarize a global motor activity expressed by the accelerometer data referred to the anatomical part on which the device is fixed. The MA_e index is computed as the standard deviation of the acceleration-modulus time series; in fact, for each epoch considered, the modulus of the three acceleration components (x, y, z) is computed for each sample of the epoch.

In particular, the selected epoch is a 1-minute epoch, so in a 24h monitoring each device proposes a set of 1440 consecutive MA_e values; overall 24 hours values are also computed.

Activity Ratio is an index designed to quantify the unbalance between activities recorded in two different body points; its definition is based on a synchronous comparison of data from different locations. In particular it is defined observing synchronously the MA_e of two different body points: once the coupled MA_e values of the two different body points are plotted in a Cartesian plane, the α angle between the quadrant bisection-line and the best least-squares fitting line passing through the origin is computed. The AR index is then defined as $AR = 100 * \frac{45° - \alpha}{45°}$.

All the computed indexes have been designed with the precise aim not to depend on the sensor orientation. Each device provides a set of raw accelerations on the three spatial axes (x, y, z) that were computed into the presented indexes through the use of MATLAB's codes. All the acquisitions were performed with a sampling frequency of 50Hz.

The experiment involved 28 healthy subjects (14 men and 14 women, aged 18 to 58 years) who underwent a 24h monitoring and compiled a set of questionnaires useful to collect handedness, demographic and lifestyle data. For each subject, and for each device (body point), we have extracted an MA_e minute-per-minute profile over the 24h, overall MA_{24h} values and AR_{24h} indexes. While the MA_{24h} are single average values for each body point, the AR_{24h}, as said, are computed as a comparison between body points, so here below the five comparisons extrapolated for each subject are listed:

- *Right upper limb vs Left upper limb - AR24h(UR,UL).*
- *Ipsilateral lower limb vs Dominant upper limb - AR24h(LR,UR).*
- *Right upper limb vs Waist - AR24h(UR,S).*
- *Left upper limb vs Waist - AR24h(UL,S).*
- *Lower limb vs Waist - AR24h(LR,S).*

The outcomes showed that MA indexes can describe coherently the limbs behaviors. The healthy subjects presented a limited difference in upper limbs average activity values (average mean difference of 8.9 mg, where $g = 9.81\, m/s^2$) depending from handedness, and this confirms the results of Rabuffetti [23] and Nagels [20]. The indexes computed for waist (i.e., center of mass approximation) and lower limb prove themselves to be linked to actual physical activity and locomotor performances ($r = 0.74$; $p < 0.001$). The ability of sacrum mobility-related index to express the amount of global activity is confirmed also observing the values proposed by the subjects when they are observed into occupational groups differentiated for an expected global daily activity (i.e., STUDENTS, OFFICE WORKERS and ACTIVE OCCUPATIONS): this suggests that it should be possible to identify thresholds used to classify the intensity of a daily activity relying on this values.

Observing MA and AR indexes, no significant differences are highlighted neither between male and female or because of the age of the subjects; not statistically significant trends evidenced that female's indexes usually show higher average values than male's indexes (but men express higher max values than women). Furthermore, the MA_e profiles proposed, if supported by a well filled daily diary, could be a good instrument for a visual analysis of the daily activity or just to compare two different body points over time.

The AR indexes extract specific information about limb prevalence consistent with what MA indexes show. The index that compares synchronously the upper limbs activity (AR24h(UR,UL)) show that in healthy subjects, even if handedness exist, in everyday activity the preponderance of the favorite upper limb on the other is extremely reduced (mean value of 7.5%); moreover, in accordance with the right-handedness of the group all subject present positive values of AR24h(UR,UL). It is worth noting that AR indexes provide a different information compared to MA indexes. For example, MA_{24h} values showed that there is not a significant difference in the daily average limbs activity when the limbs are compared between them; instead AR indexes show that a significant difference exists when the comparison is made in terms of "values of preponderance", values obtained from a comparison between the limbs activity and a common signal as the one extracted from sacrum.

Furthermore the level of preponderance can not be related to the participant's professions as is the case for MA_{24h} values which showed higher values in those subjects who have more active jobs.

Lastly, the designed AR indexes are independent from the eventual subtraction of the night period. Once the night period is deleted (21:00pm to 06:00am) and the MA_{15h} and AR_{15h} indexes computed, if we make a comparison (t-test on averages, $\alpha = 0.05$) between these 15h values and their corresponding 24h values, all the AR indexes show $p > 0.74$ while MA indexes show $p < 0.05$. This means that the subtraction significantly influences the MA values but not the AR values which remain statistically unchanged between the 24h and the 15h case. The explanation is linked to the synchronicity assumption and the α angle on which is defined the AR index: epochs with larger MA_e indexes are the most relevant for preponderance quantification, while the epochs with small MA values (e.g., sleep or resting related epochs) are expected to contribute less since the best-fitting line, used to define the index, is an eigen-vector which passes by the origin of the axes. On the other side, when the MA average indexes (24h or 15h) are computed each epoch contributes equally in the final value, whether the single MA_e values are small or big.

Again, both MA and AR indexes result reliable in describing the activity of a day for people used to a week routine: during the five retest the Δ values (test - retest outcomes) are reduced to few units; and this is interesting considering the objective variability may be present in the motor activities of a subject due to uncontrollable exogenous and endogenous factors.

After the retest session the Pearson's r coefficients between the values of the same index for the two sessions of monitoring have been computed also. Even if the retest group is limited to 5 subjects the correlation coefficients are good ($0.69 < r < 0.81$) for 4 indexes ou of 9; in particular, the indexes which involve the upper limbs are those which show the highest values. The test-retest reliability results, with the limits due to a small group, confirm what showed Rabuffetti [23] ; in any case further investigation with a larger retest group are needed.

Last but not least the acceptability questionnaire's answers confirmed GENEActiv as an advisable actigraph for mono/multi-sensor setups for motor activity assessment: even if some subjects highlighted a little bother with some devices (i.e., ankle and sacrum devices), the overall result is that GENEActiv can be considered absolutely *"comfortable"* and not able to interfere with classic daily activities.

Sinossi

Gli ultimi vent'anni hanno visto un significativo sviluppo e relativa diffusione di dispositivi indossabili e portatili (*wearable and portable devices*) all'interno del mondo sanitario e della riabilitazione motoria. La loro diffusione è legata al desiderio di migliorare e rafforzare quelli che sono i metodi di indagine comunemente utilizzati nei classici laboratori di analisi del movimento. Questi laboratori, grazie all'utilizzo di una strumentazione altamente affidabile ed accurata (es., sistema optoelettronico, piattaforme dinamometriche etc.), continuano a rimanere il riferimento essenziale per la valutazione del movimento, tanto nel mondo prettamente clinico che della ricerca; questo però non toglie che si sia ormai diffuso un largo consenso nel riconoscerne anche dei limiti. In particolare, negli ultimi anni, anche grazie all'OMS (Organizzazione Mondiale della Sanità), è stato posto l'accento sulla necessità di distinguere tanto la cosiddetta *motor capacity* quanto la *motor performance*: due elementi complementari e fondamentali per una completa analisi motoria, sia che essa riguardi persone con limitazioni motorie che persone sane. La *motor capacity* è l'abilità motoria che un soggetto è in grado di esprimere durante specifici esercizi eseguiti in un ambiente controllato e sotto la supervisione di uno staff; in sostanza coincide esattamente con ciò che viene normalmente misurato e valutato all'interno di un laboratorio del movimento (es., gait analysis, reaching test etc.). La *motor performance* è invece la performance motoria che un soggetto è in grado di esprimere durante le attività quotidiane in quelle che sono la vita e le circostanze di tutti i giorni: in questo caso si parla proprio di tutto ciò che un laboratorio non permette di valutare, data la complessità e la non portabilità dei sui strumenti classici. Prendendo in considerazione una persona con disabilità motoria, valutare la sua motor performance significa focalizzarsi su quelle che potrebbero essere le sue difficoltà quotidiane; certamente i dati forniti da una classica analisi da laboratorio sono affidabili e accurati, ma l'indagine non può definirsi realmente completa. Un esempio tipico è proprio il soggetto con disabilità che, in laboratorio si sforza di completare gli esercizi e raggiungere gli obiettivi richiesti, ma nelle attività quotidiane incontra difficoltà in attività analoghe non essendo spinto a raggiungere specifici limiti.

È esattamente in questo contesto che stanno cercando di diffondersi i dispositivi portatili e indossabili per il monitoraggio dell'attività motoria; strumenti complementari all'analisi di laboratorio grazie alla loro capacità di svincolare l'analisi dall'ambiente di laboratorio stesso verso quello che è detto un *ambiente ecologico*; non per questo devono però intendersi sostitutivi all'indagine classica.

I dispositivi portatili e/o indossabili sono molti e di diverso tipo, ma in ogni caso è possibile affermare che un interesse particolare è stato recentemente posto nei confronti dell'actigrafia. Gli actigrafi sono sostanzialmente dei dispositivi capaciti di misure l'attività motoria grazie all'utilizzo di accelerometri; altra caratteristica peculiare di questi dispositivi è inoltre la possibilità di garantire monitoraggi di lungo periodo (es. 24 ore o più), una cosa assolutamente impossibile per le indagini di laboratorio che si svolgono tipicamente in decine di minuti o poche ore e non prevedono un monitoraggio continuato, ma piuttosto un'analisi basata sulla ripetizione di specifici esercizi (es. camminare lungo una passerella).

Negli ultimi decenni l'actigrafia ha avuto larga diffusione ed è stata utilizzata e validata in numerosi contesti tra cui anche la medicina del sonno; oggi però, vista l'incidenza di alcune patologie neurologiche (es. ictus, Parkinson etc) e delle relative disabilità, l'actigrafia ha penetrato fortemente il mondo della riabilitazione motoria o della valutazione dell'attività motoria in soggetti sani. L'impatto delle patologie neurologiche è oggi tale per cui ben il 62,9% delle ricerche che coinvolgono i dispositivi indossabili/portatili in relazione a queste patologie è proprio esclusivamente orientato alla riabilitazione [28].

Lo studio presentato in questa tesi ha come obiettivo quello di costruire un preliminare quadro dell'attività motoria di soggetti sani basato su monitoraggi continui e prolungati (24h) ottenuti mediante l'uso di indici motori appositamente progettati.
In particolare sono stati svolti dei monitoraggi con l'utilizzo di un set di quattro dispositivi (*GENEActiv Original*) basati su tecnologia accelerometrica triassiale MEMS.
La configurazione utilizzata per i monitoraggi prevede la presenza di un dispositivo per ciascun arto superiore al livello dei polsi, un dispositivo in prossimità dell'osso sacro (fissato grazie ad una cintura elastica) e un ultimo dispositivo ad una caviglia (la caviglia scelta è funzione della dominanza manuale del soggetto).

Gli indici motori definiti sono i seguenti:

- Indice Motor Activity MA_e, definito per singola epoca di acquisizione (declinato anche nella forma di valori medi riassuntivi sulle 24h, MA_{24h}).
- Indici Activity Ratio AR_{24h}.

L'indice Motor Activity è una variabile legata all'epoca di acquisizione prescelta ed è capace di riassumere l'attività motoria globale del punto corporeo (es. arto) a cui si riferisce l'accelerometro da cui sono estratti i dati; l'attività media, come detto, può essere relativa alla singola epoca (MA_e) o all'intera registrazione (MA_{24h}). L'indice MA_e è calcolato come la deviazione standard della serie temporale dei moduli dell'accelerazione; infatti, per ogni epoca, è calcolato il modulo dell'accelerazione nelle tre componenti spaziali (x, y, z) per ciascun campione relativo all'epoca stessa. L'esperimento ha visto scelta un'epoca di 1-minuto, dunque, ipotizzando dei monitoraggi di 24h, ciascun dispositivo fornisce un insieme di 1440 MA_e consecutivi

L'indice Activity Ratio è invece pensato per quantificare una preponderanza di attività quando due punti corporei, cui i dispositivi riferiscono, sono confrontati. Nello specifico, vengono accoppiati i valori sincroni MA_e per i due siti di misura che si desidera confrontare, quindi si rappresentano le coppie di punti su di un grafico cartesiano: detto α l'angolo tra la bisettrice del quadrante e la retta ai minimi quadrati passante per l'origine relativa ai punti rappresentati, l'indice AR è definito come $AR = 100 * \frac{45° - \alpha}{45°}$

Tutti gli indici descritti sono stati progettati con la precisa volontà di renderli completamente indipendenti dall'orientazione degli accelerometri, ma esclusivamente dipendenti dalla loro posizione (posizionamento corporeo). Ciascun dispositivo fornisce come output le accelerazioni sui tre assi spaziali (x, y, z), mentre gli indici descritti sono ottenuti elaborando queste accelerazioni tramite appositi codici MATLAB. Tutte le acquisizioni hanno visto una frequenza di campionamento di 50Hz.

L'esperimento ha coinvolto 28 soggetti sani (14 uomini e 14 donne, di età compresa tra 18 e 58 anni) che si sono sottoposti ad un ininterrotto monitoraggio di 24h durante una comune giornata lavorativa; ai soggetti è stato anche chiesto di compilare una serie di questionari utili alla raccolta di dati demografici e relativi allo stile di vita. Per ciascun soggetto, e ciascuno dei quattro dispositivi indossati, sono stati estratti un profilo MA_e minuto-per-minuto lungo 24h, valori medi MA_{24h} e indici AR_{24h}.

I valori medi MA_{24h} sono dei valori singoli riferiti a ciascuno dei quattro dispositivi, gli indici AR_{24h}, vista la definizione, sono invece valori che possono essere estratti da un confronto tra punti corporei; in particolare gli indici AR_{24h} estratti per ogni soggetto sono elencati a seguire:

- *Arto superiore destro vs Arto superiore sinistro - AR24h(UR,UL).*
- *Arto inferiore ipsilaterale vs Arto superiore dominante - AR24h(LR,UR).*
- *Arto superiore destro vs Bacino - AR24h(UR,S).*
- *Arto superiore sinistro vs Bacino - AR24h(UL,S).*
- *Arto inferiore vs Bacino - AR24h(LR,S).*

I risultati mostrano la capacità degli indici MA di descrivere con coerenza il comportamento motorio degli arti e dei punti corporei acquisiti. I soggetti sani presentano una differenza limitata tra le attività medie dei due arti superiori (differenza media di 8.9mg, dove $g = 9.81\, m/s^2$) benché una dominanza manuale esista; questo conferma alcuni risultati già ottenuti da Rabuffetti [23] and Nagels [20]. Gli indici calcolati per il sacro (ossia l'approssimazione del centro di massa) e l'arto inferiore si dimostrano direttamente collegabili all'attività fisica svolta e alle attività locomotorie giornaliere ($r = 0.74$; $p < 0.001$). La capacità dell'indice legato al movimento del centro di massa di essere espressione dell'attività motoria globale è confermata anche dall'osservazione dei soggetti quando questi sono suddivisi in sottogruppi legati alle rispettive occupazioni (es. STUDENTI, IMPIEGATI e LAVORATORI ATTIVI): si potrebbe ipotizzare di definire delle soglie di classificazione dell'attività fisica giornaliere basate proprio su questo indice.

Nessuna significativa differenza è stata individuata quando gli indici sono comparati tra i sessi o in relazione all'età dei soggetti; in ogni caso è bene sottolineare che le donne presentano valori medi tendenzialmente maggiori di quelli maschili (anche se i maschi presentano massimi maggiori). Inoltre, i profili MA_e lungo le 24h, se supportati da diari di attività quotidiana ben compilati, possono essere un ottimo strumento per una analisi visiva dell'attività motoria o, più semplicemente, un buon strumento di confronto tra punti di misura distinti.

Gli indici AR permettono l'estrazione di informazioni di prevalenza coerenti con ciò che viene mostrato dagli indici MA. L'indice AR che compara in modo sincrono i due arti superiori mostra che, in soggetti sani, esiste una prevalenza molto limitata tra i due arti durante l'attività giornaliera (valore medio 7.5%), benché ovviamente esista un arto preferito: coerentemente al fatto che il gruppo è costituito da soggetti destri questo indice AR24h(UR,UL) mostra sempre valori positivi. Gli indici AR rappresentano un'informazione differente dagli MA: un esempio è quello in cui non si evidenziata una significativa differenza tra i valori medi di attività per gli arti superiori (valori MA_{24h}), ma la si nota invece quando anziché comparare i valori medi di attività si comparano i livelli di preponderanza degli arti superiori rispetto al sacro. Inoltre, i livelli di preponderanza non mostrano legami con l'occupazione del soggetto e quindi l'attività motoria mediamente svolta in una tipica giornata.

Gli indici AR esprimono anche un'informazione indipendente dalla sottrazione del periodo notturno dall'acquisizione originale: si osserva che quando questo periodo di tempo è eliminato (21:00pm a 06:00am) gli indici AR non mostrano significative variazioni nei confronti dei loro corrispettivi calcolati sulle 24h (tutti $p > 0.74$ quando è eseguito un t-test); cosa non vera qualora il confronto coinvolga gli indici MA (tutti $p < 0.05$), che sono, invece, fortemente influenzati dall'eliminazione di questo intervallo temporale. La spiegazione è da rintracciarsi nell'assunzione di sincronicità e nell'angolo α su cui si basa la definizione dell'indice AR: dal momento che l'angolo è definito utilizzando un retta ai minimi quadrati passante per l'origine, le epoche con piccoli valori MA_e (es., le ore di sonno o di attività di riposo) sono meno influenti nel definire il valore finale dell'indice rispetto a quanto non siano le epoche con MA_e più intensi.

Tutto questo non è invece vero quando si considerano gli indici MA medi (24h o 15h) che essendo delle medie aritmetiche vedono pesare ugualmente i piccoli o grandi valori MA_e relativi alle singole epoche.

Entrambi i tipi di indici, MA e AR, risultano affidabili nel descrivere l'attività motoria giornaliera di soggetti soliti ad una certa routine. Quando vengono comparati i valori delle sessioni di test e retest per i 5 soggetti sottoposti al retest, i valori Δ (risultati test - retest) sono ridotti a pochissime unità; elemento interessante considerando l'intrinseca variabilità motoria che un soggetto può esprimere a causa di non gestibili fattori esogeni ed endogeni che affliggono la giornata.

Data la sessione di retest sono anche stati calcolati i coefficienti r di correlazione tra il medesimo indice nelle due acquisizioni test e retest. Benché il gruppo di retest abbia dimensioni limitate (5 soggetti) i coefficienti sono buoni ($0.69 < r < 0.81$) per 4 indici su 9; in particolare, sono gli indici che coinvolgono gli arti superiori a mostrare i valori maggiori. I risultati di questo confronto sull'affidabilità test-retest, pur dato un piccolo gruppo, sembrano confermare i risultati mostrati da Rabuffetti [23]; in ogni caso sono necessarie ulteriori indagini provenienti da un gruppo di retest più ampio.

Ultimo, ma non per importanza, il dispositivo GENEActiv utilizzato si attesta come fortemente consigliabile, in termini di *"comodità"*, in monitoraggi prolungati del movimento che coinvolgono setup mono o multi-sensore: benché alcuni soggetti abbiano segnalato leggeri fastidi in relazione ad alcuni dispositivi (es. quelli posizionati alla caviglia e sul bacino), globalmente la soddisfazione è condivisa e GENEActiv è considerabile del tutto confortevole e incapace di interferire con l'esecuzione di comuni attività quotidiane.

1. Rehabilitation engineering and wearable devices

1.1 Introduction

Today several innovative technologies, systems and solutions support the medical approach towards the evidence based medicine (EBM), which can be defined as *"the conscientious, explicit, and judicious use of current best evidence in making decisions about the care of individual patients."* [30]. Therefore EBM means a medical approach based on the scientific and statistical analysis of risks and benefits of medical treatments, with the target of a more aware participation in the phases of diagnostic investigation, therapeutic intervention and, in general, in the medical decision process. The extension of this approach from the research sector to the healthcare field brings an evidence based healthcare: the development and systematic use of clinical guidelines to assist practitioners about appropriate health care in specific clinical circumstances.

One of the areas which had a significant evolution in the last 20 years, is the one concerning functional evaluation and rehabilitation, because of a technological development providing a great number of accurate and reliable instruments able to produce a whole new kind of data and information; so that the quantitative data and information besides a well designed and conducted research are now foundation of modern rehabilitation medicine.

The maintenance of a good state of health, without any kind of disability or impairment, depends on a wide set of variables, between which there are the compliance to an adequate standard of living or, also, the chance to access to a structured and good working healthcare system. In accordance with the definition by WHO [34][35], rehabilitation is the implementation of all possible means to reach the development of the maximum potential of an individual on his physical, sensory, intellectual, psychological and social level, with the aim of a maximum independence, full inclusion and participation in all aspect of life.

In a strictly medical context, rehabilitation has targets that can be recap as follows:

- *Recovery of the compromise functions, in the limits of therapeutic possibilities.*
- *Reduce to a minimum every possible form of disability.*
- *Avoid the possibility that disability turns into handicap, thus a real disadvantage in social relationship.*

Once observed the proper medical definition of rehabilitation, aware of the brand new approach allowed by new technologies in the rehab-machine, it is clear that engineering assumes different purposes, so that it is common to refer to it as *rehabilitation engineering*.

In accordance with what is said in this introduction its targets are synthesizable in two main points:

- *Provide instruments and methods able of quantitative (no more just qualitative), repeatable and reliable investigations.*
- *Provide a methodological and technological support to the medical decision process of intervention.*

1.2 The Functional Evaluation Laboratory

Even though the last two decades have shown a spread of advanced medical technologies, still today not completely quantitative approaches are common in the assessment of pathologies: a classical example are questionnaires and scales for clinical assessment of diseases and their consequences (e.g., motor impairments), widely used in the healthcare. The MMSE (Mini–Mental State Examination) used to measure cognitive impairment, the Vanderbilt ADHD Diagnostic Rating Scale, a self-report assessment tool for ADHD (Attention Deficit Hyperactivity Disorder), the UPDRS (Unified Parkinson's Disease Rating Scale) for the clinical study of Parkinson's disease or the EDSS (Expended Disability Status Scare) used to quantify disability in multiple sclerosis, are just few out of the countless scales and questionnaires used everyday in the healthcare world.

These tools, self reported by patients or not, were designed to make simpler and easily comparable pathologies assessments in specific contexts, but even if these instruments are certainly a good way to assess peculiar aspects of pathologies and disorders or describe a clinical situation in general terms, they are at the same time completely qualitative items, unable to measure all the relevant aspects [7][9][24].

What is worth noting is that scales are highly affected by inter/intra-operator variability and are dependent on the operators' experience. Moreover they need to be specific to the assessed feature, need to be reliable, need to be repeatable and with a suitable resolution for the evaluation of the possible clinical board fluctuations, but all these features are often difficult to reach. A similar concern is possible for self-reported questionnaires: usually overly generic and dependent on the patients interpretation and subjectivity.

These clinical tools are not to be abandoned, but in a modern conception of medicine they must be supported by technologies able to provide quantitative data and information, therefore instruments with the same target of scales, but, thanks to the technical evolution, capable of better performances in terms of sensitivity, repeatability and reliability.

Speaking about motor rehabilitation, the task of conducting a quantitative and reliable motor investigations using advanced medical technologies is entrusted *to motor analysis laboratories*. These laboratories evaluate the human movement in relation to motor disability or motor performance (e.g., sport activity) and thus provide data exploitable to improve treatments. The technologies that could be found in these labs allow what is known as *functional evaluation study*: an analysis based on the measure of a series of parameters able to describe, directly or indirectly, different motor qualities. Professional workrooms are set with devices that can ensure an high quality *multifactorial analysis*: multifactorial means that the operators can obtain, at the same time, data about temporal parameters, kinematic, kinetic and muscles activity. All the laboratories investigations follow some standardized procedures which make the results highly comparable.

Gait analysis has today reached an exclusive role, however it is important to remember that all these laboratories are de facto moldable to all kind of motor tasks and necessities if properly set: gait analysis, even if is the most widespread approach to movement evaluation, is just a finite area of the wide world of quantitative movement analysis.

Inside the functional evaluation laboratories, bulk of the work is entrusted to three main devices. Below are presented their brief descriptions without dwelling on specific technical aspects; these three main devices are:

A. **The Optoelectronic system.**
B. **The Kinetic-platform.**
C. **The EMG technology.**

A. An optoelectronic system (example scheme in **Fig.1.1**) is a system which enable to compute a wide amount of kinematic variables (i.e., step length, duration of stance and swing phase, kinematic joint angles, walk speed etc.) thanks to the reconstruction of the body movements in a virtual space. The movement reconstruction is possible thanks to a group of cameras operating in the infra-red spectrum: these cameras, associated with markers placed on studied anatomical points of the patient, and thanks to known protocols, compute the body displacement observing the markers displacement in space.

A correct use of this device requires an aware calibration, the knowledge of the proper modalities of acquisition and a critical interpretation of outcomes, without which all data can be completely useless or misunderstood.

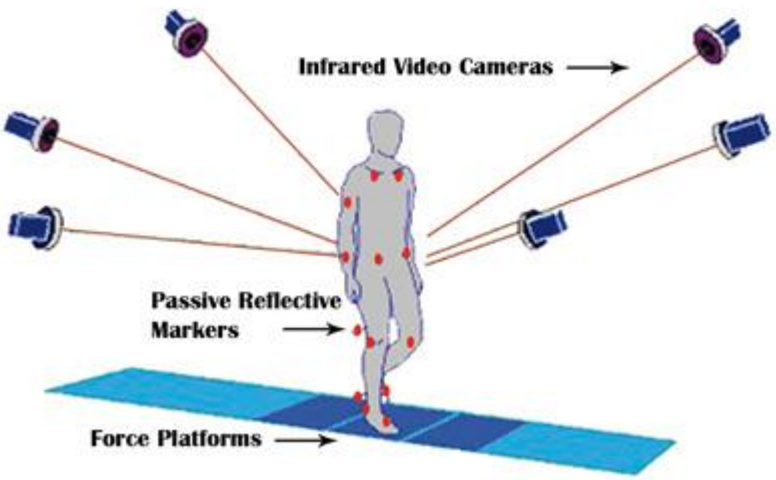

Fig. 1.1 - Optoelectronic system example scheme.

N.B.: optoelectronic systems are complex devices and it is possible to classify them trough their features (e.g., active and passive systems) or speak in depth about their functionalities; however, a full discussion on this instrument is not the focus of this thesis and so this theme will not be deepened. Similar considerations should be made about the next points **B** and **C**; this wants to be just an introduction to movement laboratories.

B. The evaluation of kinetic variables is done using devices able of measure forces and pressures between the subject and the external world. The kinetic platforms (or force platforms) are devices of this class: through force transducers (i.e., strain gauges or piezoelectric technology), positioned in load cells, allow to compute the reaction forces generated by the interaction of the subject with the platform during the requested task (e.g. walking). In particular the force platform returns the reaction forces at the ground in terms of amplitude, spatial orientation and point of application and their variation over time.

The forces involved during a walk are: ground reaction forces, inertial forces etc.; once the ground reaction is measured in its three spatial components, combining it with the kinematic data is possible to solve the inverse dynamic problem and so obtain all the dynamic variables of interest: joints' moments and powers.

C. EMG technology completes the multifactorial information a motion analysis lab can provide: thanks to an EMG acquisition one can obtain data not available from other instruments as data about the timing of muscle activity and about the muscles involved in the motor acts. Furthermore, today EMG devices are largely less non-invasive than in the past, thanks to modern transmission data protocols which allow a substantial removal of all cables, so that a modern EMG system is substantially composed just by the muscle electrodes and a control unit able to receive the data. Performing an EMG test properly implies a correct placement of the electrodes, a practice less simple of what one may expect because of the easiness with which the outcome can be disturbed.

N.B.: differently from what one may think, an EMG measure can not provide information about the muscle contraction force.

Fig.1.2 - Example of a portable wireless set for EMG.

All the technologies described above are the minimum required to obtain a satisfactory functional evaluation, however, it is worth noting that there are a lot of other devices to place side by side with those described. Devices able to provide complementary and different information, examples are: dynamometers to observe muscle forces, ergometers to measure the mechanical work expressed during a motor task, metabolimeters to evaluate energy expenditure.

1.3 Wearable devices in rehabilitation

Even if the modern motion analysis laboratories allow a non-invasive, reliable and complex (in terms of amount end quality of data) medical investigation, they are not free of bugs or imperfections [7][29][32]. As previously highlighted, with the aim of minimizing technical errors, a great attention is put on the respect of protocols and standards; this, however, can not avoid movement artifacts, calibration approximations or the limitations of the adopted protocol. Furthermore a limit is represented by the laboratory setting itself. The lab is an highly controlled environment and this is a good and bad feature at the same time; from one side you can ensure high quality data because of the use of advanced technologies, by the other, the lab can warp the patient's motor performance due to the artificial setting of the experiment [19]. Considering in particular motor impaired subject, it is not to be underestimated the physical effort required to undergo to a laboratory survey, which requires time and a certain amount of commitment and attention by the patient.

At this point it is interesting to underline the deep difference between the notions of *motor capacity* and *motor performance* as described by the *International Classification of Functioning, Disability and Health (ICF)* drawn up by the World Health Organization [16]:

- **Motor capacity**: *refers to the ability - the motor potential - a subject is able to express during specific motor exercises and tasks performed in a controlled environment, under the supervision of professional staff, just as in a laboratory set.*
- **Motor performance**: *namely the motor potential the subject expresses during every day life activities in a free-living environment.*

While the former is exactly what is commonly observed into a laboratory setting, the latter matches exactly with what the laboratory instruments can not detect. About this issue, in modern rehabilitation, is becoming more and more clear how in the past the focus was overly oriented on the capacity component, trying, after the impairment, to improve the body motor ability just in relation to laboratory tasks, neglecting the everyday difficulties a disabled subject may have to deal with.

In this scenario takes great importance the world of *portable and wearable devices*, which can partially free the analysis from hospitals and research centers in favor of investigations centered on the individual and the environment he deals with everyday: in this terms one usually speaks about *ecologic environment***.** It is worth noting that this can involve both pathology-related investigations that performance surveys as those related to professional athletes.

Today exists a large amount of instruments, not necessarily to be worn, which can help in moving the analysis outside the laboratories; below some indicative examples and related images are presented:

- Mobile platform with pressure sensors; not to be confused with kinetic-platforms, this device displays a static or dynamic distribution of contact pressures, but not the ground reaction forces.
- Heart rate monitors.
- Portable systems for energy expenditure assessment.
- Actigraphs.

Fig. 1.3 - K4b^2 by COSMED, example of portable ergospirometer.

Fig. 1.4 - Example of a heart rate monitoring system by GARMIN; this model is composed by a wristwatch and an elastic sensored chest-band.

Wearable devices, of our interest because protagonist of the experiment described later, are many and of different types, but all of them share some common features listed below:

- **Easily wearable**: these devices must be worn without particular troubles. Uncomfortable devices would not be easily accepted by the subject who needs to wear them or could also make the subject in trouble with a correct positioning.
- **Portable**: the use outside the lab is the pith itself of these instruments, they must be able to be easily transported and so used in different contexts.
- **Light and contained in dimensions:** the devices must be able to be worn by young people, old patients or athletes depending on the study, but in any case they must not interfere with the execution of the motor activity. If this feature is not respected the results can be affected of distortions from the ideal measure. In summary, the person under investigation - often physically impaired - must never be hindered in the execution of tasks.

- **Mass storage system and/or transmission of data system**: being wearable, these devices need a transfer of data for the elaboration; this can be done with the equipment of storage mass (which extension influences the maximum duration of measure) or of a system for a data transmission in real time with the execution of the survey (e.g. Wi-Fi EMG devices).

Wearable systems not only ensure monitorings out of labs, but also provide the possibility of *long-time measurements*: continuous and extended acquisitions are not possible with the instruments used in a classic laboratory. A typical gait analysis or motor investigation carried out with optoelectronic systems, kinetic-platforms and EMG, takes minutes (not considering the preparatory stages) and derives motion information from a motor task (e.g. walk, reaching, hand to mouth etc.) repeated a moderate number of times (further element of stress for a patient). Wearable devices allow an approach completely different able to investigate, for example, a 12h, 24h activity or more without requiring the execution of particular tasks or exercises, leaving the subject free to approach the everyday activities as he is used to; this deeply modifies the information you can obtain from the motor analysis.

Therefore, if the interest is directed to an analysis of a motor behavior in the daily living, because it can help understanding good or bad habits, difficulties and behaviors of physically impaired people, it is essential to have available devices able of measures with large temporal windows of acquisition: a person, in his habits, is active through several hours during the day, so a long-time monitoring is the only plausible way of assessment in this view. A same reasoning could be done for monitoring pathologies as those related to sleep, really common disturbs that from some years can be partially investigated even without the complex instrumentation of the gold standard polysomnography.

What has been just said does not mean that wearable devices can replace the laboratory technologies or provide data fully comparable to their highly specific kinetic and kinematic variables; usually wearable systems offer just raw data usable for coarser or global assessments. What we wanted to highlight, is that motion analysis lab represents today an indispensable tool in the world of healthcare and rehabilitation because of the data it can provide and how it helps in the medical process of intervention; but, on the other side, is also important to be aware of its limits and how they can be compensate with the use of wearable and portable system (which are not a substitute).

1.3.1 Actigraphy

Actigraphy, today, is probably the largest sector concerning wearable devices and thanks to the technological advancements it is present in completely different areas: from proper healthcare to everyday sport activities or professional sport, involving athletes and their performances. Basically, *actigraphs* (also called actimetry sensors) are able to detect gross movements of the person wearing them thanks to accelerometer sensors as those that will be described in **Chapter2**; this actigraphs are devices able to provide both data in the form of "proprietary count-unit" and raw data as the accelerations in 3D-space. This makes the actigraphs technology useful for non-invasive monitoring and study of physical activity and rest-activity cycles behaviors and their relationships to chronic health conditions such as obesity, diabetes, cardiovascular disease, sleep disorders or motor impairments [9][24].

In general terms an actigraph is composed by the following elements:

- Accelerometer/s; based on sensors of some kind of technology (**Chapter 2**).
- Pre-processing apparatus, i.e. a low-pass filtering system and/or a system to compute proprietary evaluation indexes of movement.
- Data storage.
- Physical interface (e.g. USB port) or data transmission protocol for data transfer.

some devices can be more complex and integrate other feature as start/stop buttons, gyroscopes, magnetometers, temperature sensor and light sensor which can help in integrating the measure with more information (e.g., gyroscopes can provide information about angular velocities, while magnetometers can provide data about directions acting like compasses).

The ability of wearable systems to evaluate non common aspects of physical activity because of their accessibility and handiness in everyday activities, was understood since the '70s, when thanks to the first miniaturization of technology these devices began spreading: accelerometers began to be used to study gait and other movements, or for the measurement of tremors and motor activity in neurological patients [3]. In 1979 Laporte et al. [18] described a "Large-scale Integrated Motor Activity Monitor", a device wearable at different body locations and not invasive during daily activities; this is one of the first example of a wearable system which the authors describe as able to discriminate activity differences between individual and population, and so potentially useful in healthcare investigations as those related to motor activity limitations due to pathologies or risk factors (e.g., acute heart disease, obesity). The diffusion of these systems involved many health areas [3][10][24], even the one related to sleep: in 1989 Sadeh et al. [20][26] proposed one of the studies out to confirm the effective use of actigraphy in sleep studies and in the monitoring of circadian rhythms; the outcome data obtained by Sadeh resulted enough valid and reliable to discriminate between the different sleep states: actigraphy was so validated as a plus instrument in support of the standard polysomnography, at least in a first screening phase. The sleep sector, in relation to potential actigraphy contribution, is still today largely investigated either in terms of the many sleep disorders (e.g., obstructive sleep apnea, restless legs syndrome etc.) or of a greater comprehension of circadian rhythms, as shows the study of Natale et al. [21] about handedness and lateralization of hemispheres activity during sleep.

In the 90's and 2000's, wearable systems definitively penetrates the rehabilitation research area because of the need to dispose of instruments useful in the assessment of motor impairments, loss of mobility and reduced independence deriving from neurological pathologies and old age [28]: this brought to different, and not always according, results in their usage; even today this world need to be carefully explored in search of a shared standard in terms of positioning, reliability and usability of wearable devices and of the data they can provide [5][31]. The study of Nagels at al. (1996) [20] is a clear example of how the interest in actigraphic measures, with time, led to the desire of investigate really specific aspects of this world, and not just the will to validate the instruments. In particular, the aim of the study by Nagels was to evaluate the influence of lateralism on actigraphically measured motor activity. This element is relevant still today, it is not difficult to find recent studies that use a unique monitoring device, this is usually worn on the non-dominant upper limb even if a reason, except the subject's comfort, is not mentioned: it is plausible imagine an influence over measures in relation to the limb observed due to laterality, and this is a feature not to be ignored in acquisitions involving the use of a single device. Negels showed a statistically significant correlation between actigraphic parameters and a standard technique for the evaluation of handedness as the *Edinburgh Inventory Handedness Scale* [22]; the differences found between dominant and non-dominant wrists are highly significant but small. In particular, thanks to the two main parameters computed by Negels (Activity Index AI and Movement Index MI), seems that if we compare dominant and non-dominant wrists, there is a larger difference in pattern of movement than in total motor activity.

Even if in the decades actigraphs have been used in different contests as the one related to sleep medicine, nowadays the focus is on motor disability assessment derived from multiple pathologies (stroke above all) and physical activity assessment (in healthy people too, as in the study presented in this thesis). The systematic review led by Steins et al. [28] shows the impact of motion-sensing technology to assess functional activities in neurological and non-neurological conditions: for example stroke represents the 43.5% of literature about this topic when speaking of neurological disease (the other big slice is Parkinson with 34.5%), furthermore the researches are specifically oriented in rehabilitation in the 62.9% of cases concerning neurological diseases.

Neurological disorders can easily result in mental and physical disability involving different body areas. The number of cases deriving from these disorders is wide and differentiated, therefore it is possible to identify hemiplegic, diplecic or tetraplegic in relation to the limbs involved; the possible classifications of physical impairments can also be more detailed and involve even the muscle tone or the residual coordination of subjects, so you can speak about: spastic forms, ataxic forms, diskinetics forms, and so on in relation to the characteristics and capacity of the subject involved.

The quantitative assessment of these different impairments involving the limbs is a fundamental element of any rehabilitation program; in the past, but even today, clinical scales were the most diffuse tool for the assessment of limb in subject hit by neurological pathologies: examples are the FMA (Fugl-Meyer Assessment of Physical Performance), BBT (Box and Bock Test) or ARAT (Action Research Arm Test), all considered reliable and of proven effective in the evaluation of motor function, but unable to provide real consistent data because of their qualitative (or not perfectly quantitative) nature. About this topic Gebruers et al. [9] proposed a prospective study to investigate the validity of actigraphy in stroke comparing accelerometers variables with two validated and reliable stroke scales as the National Institute of Health Stroke Scale (NIHSS) and the FMA.

The results significant correlation between accelerometers outcomes (i.e., ration between arms activity and activity of the impaired arm - AIA) and NIHSS (ratio $r = -0.59$, AIA $r = -0.75$; $p < 0.001$) and FMA (ratio $r = 0.54$, AIA $r = 0.69$; $p < 0.001$). According to Gebruers, these correlations between the actigraphy outcomes and the frequently used validated scales, demonstrate that actigraphy is a simple, valid, objective and reliable clinical research tool able to discriminate less impaired from more impaired patients.

Previously was mentioned the impact of stroke in the wide set of neurological diseases, or at least the interest that it recalls in the rehabilitation research area: an easily understandable interest if some data are observed. Annually, 15 million people worldwide suffer a stroke; of these, 5 million die and another 5 million are left permanently disabled, placing a burden on family and community [35]. The incidence of stroke is declining in many developed countries, largely as a result of better control of high blood pressure, and reduced levels of smoking, however, the absolute number of strokes continues to increase because of the ageing population [35].

The incidence of stroke and the incidence of disability as its consequence (NB.: stroke is the main cause of long-term disability in the western society) made the wearable devices world truly interested in this pathology and its rehabilitation: the impaired muscle function deriving from stroke leads to a situation in which one-fifth of survivors do not regain functional activity in both arms, and half of the patients with initial severe paresis do not gain any important function of the more affected arm; furthermore the learned non-use of the paretic arm is a common consequence that further reduces the level of functioning [29]. So actigraphy assumes a central role in the rehabilitation: it can be a tool able of more peculiar discrimination, than the scales, and so a value more in patients' progress in the rehabilitation program and one more instrument in the medical decision process of intervention.

In 2005 Uswatte et al. [32] tried to evaluate the reliability and validity of accelerometry for measuring upper-extremity rehabilitation outcome; in particular the experiment was oriented on the outcome of patients under CIMT (Constraint-induced Movement Therapy), a rehabilitation method that tries to improve the use of an impaired arm forcing its usage due to a constriction of the healthy (or healthier) arm.

Participants have worn a system of 4 accelerometers for 3 days before and after two weeks of CIMT; the devices have been placed on both wrists, ipsilateral ankle to the more impaired arm and chest-side of the less impaired arm. In the treatment group, there was a significant increase from pre- to post-treatment of the ratio summary variable (mean change 0.08 ± 0.09; $p < 0.05$), while in the no-treatment group the change was not significant [32]. The study is a preliminary evidence of the validity of accelerometer technology for measuring upper-extremity rehab outcomes in chronic stroke subject with mild to moderate arm impairment; another important consideration regards the safety, ease of use and non invasive approach of accelerometers that have allowed 3 day long acquisition without troubles or bothers.

De Niet et al. [7] have focused the attention on the importance of both performance as well as capacity in the evaluation of subacute or chronic stroke subjects during rehabilitation of upper-limp functions. This is a clear example of what the actigraphy could bring to the world of motor rehabilitation: many are the objective and quantitative tools have been developed to test a patient's capacity after stroke (e.g., ARAT), but performance in daily life has not yet received much attention, also due to a lack of real valid instruments. The study have used the Upper-limb Activity Monitor (ULAM), developed by Schasfoort et al. [27], in its version adapted for stroke patients (Stroke-ULAM) that contemplates also electogoniometers not present in the original version of the device. ULAM is composed of 5 piezoresistive accelerometers to be placed on thighs, sternum and upper limbs. As the experiment was set, the ULAM had two main outcomes: a value called *level of usage*, namely an absolute measure for each upper limb and an other value called *proportion level*, namely a relative measure indicating the level of usage of the affected upper limb compared with the unaffected one. The outcomes have showed how ULAM is enough sensitive to detect differences between upper-limb usage in moderately recovered stroke patients, well-recovered stroke patients and control group (the control group was in this case of only 5 subject.): in all subjects the level of usage of the affected upper limb was significantly lower than the level of usage of the unaffected upper limb ($p < 0.01$).

One interesting element, as introduced before with Nagels [20], is the one related to hand preference and its impact on motor performance, even more if associated with hemiparetic stroke patients. This topic was studied by Rinehart et al. [25] with the purpose to determinate if the right arm is used more frequently in right-handed patients with stroke. What is showed is that the ipsilesional arm use was greater after right hemisphere damage than left hemisphere damage; the left hemisphere damage group used both arms together more often than the right hemisphere damage group but less often than the control group. This findings emphasize the influence of hand preference on arm use after stroke for the ipsilesional but not the cotrolesional arm, proving the complexity of the theme and the different ways it could be approached and assessed

Furthermore wearable devices can today provide raw data at the end of an acquisition, the accelerations on three oriented axes (x, y, z) are the simplest example. Therefore the set of analysis techniques available is really wide; in clinic and assessment of human movement it is still unclear which approaches are preferable to other, just because of the non unique information you can extract computing differently these data. For example Hurd et al. [15] suggest an approach in evaluating functional use of the extremities, different from the more common ratio-based approach between actigraphic recordings: usually defined some movement indexes the analysis is based on simple ratios and comparisons of level of these indexes [20] [27] . Instead, the approach by Hurd is based on the concept of entropy, already used in other health areas (e.g. cardiology): the basic idea is that an unimpaired human movement is more complex than a pathological movement and so the *sample entropy* measures a state of randomness linkable to the health of a limb; in association with classic statistical variables and asymmetry measures this could be an example of additional tool to understand what is deemed a desirable variability and how a same problem can be approached in different ways.

Whether from one side actigraphy it is proving to be a useful new instrument in motion analysis of people impaired by different pathologies, by the other side the possibility to assess physical activity and performance outside a clinical lab allows to combine the wearable devices even with a not, or slightly, pathological population. The importance of avoid an extreme sedentary life is largely shared and actigraphy can be also a valid tool for evaluating the perceived health of young, middle-aged and elder people as well as disabled [6][31]: in fact, even in absence of overt pathologies, motor abilities can deteriorate, modifying quality of life in everyday activities (elders and obese are a typical example). Regular physical activity is important for maintaining health, but 60% of global population fails to achieve the minimum of physical activity recommendation [33]; many studies, for example, investigated the association of level of daily physical activity with the occurrences of falls in elderly population [12].

As in the clinical context of stroke or other neurological diseases, mobility and (light)-disability in the activities of daily living (ADLs) are often studied through the tool of questionnaires and self-reports [31] where the subject is asked whether he has difficulties or needs help in performing basic actions.

Van den Berg-Emons et al. [33] proposed a study with the aim of give an overview of the impact of a variety of chronic physical conditions on accelerometry-based levels of physical activity, identify high risk conditions and compare the objectively assessed level of physical activity in such people with levels of physical activity previously estimated by rehabilitation physicians. In conclusion, only few of the chronic condition considered do not affect everyday physical activity in a negative way; furthermore they demonstrated how, in comparison with an objective measure made with accelerometer-technology, the physicians' ability to estimate correctly the amount of physical activity in the subject is not always good: tending to under- or over-estimate the level of activity in association with a pathology rather than another; for example there was a tendency in overestimate the activity in the groups with the more severe impairment among those considered, as the ones with spinal cord injury.

In this scenario becomes interesting an approach based not only on the measure of the amount of activity, but also on the ability of wearable devices to discriminate and recognize the single physical activity or even estimate the energy expenditure associated with a performance [6][12][17]. Gupta and Dallas [12] offer a brief discussion about some approaches thought with this aim: these ADLs classification methods vary in terms of number of accelerometers used (from 6 to only 1 device), number of ADLs detectable and accuracy, but still today does not exist a widespread agreement on what is the best approach. The method developed by Gupta and Dallas themselves uses a single MEMS 3-axial accelerometer wore at the waist level.

The results from the activity recognition on the little sample of subjects shows high accuracy (the overall accuracy of the system is 98%) for all the considered activities (Jump, Run, Walk, Sit-to-Stand, Stan-to-Kneel-to-Stand); of course the number an kind of ADLs recognizable is strongly dependent on the number of devices used.

One last interesting point of focus, concerning actigraphy and physical activity evaluation, is the one related to the estimation of Energy Expenditure (EE) during activities. EE is one of the most used variable to quantify and interpret physical activity and if actigraphy is proven adequately capable to estimate it, one can imagine new different uses for this technology; an example could be the monitoring of EE in subject who need mobility aids in everyday activities, without involving them in complex laboratory analysis with uncomfortable devices.

Between the method have been developed in the past to estimate EE from actigraphy, one can classify them into two main categories: *counts-based estimation methods* and *activity-specific estimation methods* [2]; the former are independent from the activity which is performed, the latter expect a first step in which activities are classified into clusters according to some criteria and then a second step consists in applying the proper estimation method. Understandably counts-based methods do not fit properly all activities, bringing an output not completely accurate. According to Altini et al. [2] , although different approaches have been studied there is still not consensus on how use the accelerometers, in terms on number and location on body, in studies designed to classify activities and estimate EE. Some studies investigated the accuracy of sensors placed on different part of the body in relation to the ability of detect a set of activities, but typically no one assesses how number and position of devices affect EE estimation.

Altini analyzed the estimation error from three common EE estimation approaches, furthermore studied different possible combination of five accelerometers on body and their impact on activity recognition and EE estimation. They concluded that choosing the best performing single sensor does not reduce EE estimation accuracy even compared to a 5 sensors system. In particular, if properly chosen, two sensor are sufficient for an accurate (98% with chest and wrist sensors or chest and thigh) activity recognition; EE estimation error can increase up to 88% if a non optimal sensor location is chosen, this is due to the fact that errors are mainly due to misclassification of activities.

Also DeGroot et al. [6] shows issues in obtain a satisfying EE estimation: the energy expenditure seemed not to be valid when compared with the EE calculated value from the oxygen uptake. Several studies validated the energy expenditure estimated by accelerometer data with a criterion (oxymetry or doubly-labeledwater) and all concluded that estimating the energy expenditure by accelerometry does not seem to be an adequate method or, at least, it is a topic that needs further studies.

In conclusion, it is possible to say that accelerometry-based sensing technologies have been successfully implemented in the field of rehabilitation and physical activity assessment, allowing investigations on aspect difficult to treat heretofore, in particular in relation to long-term acquisitions and ADLs. Researchers can distinguish healthy from non-healthy subjects and classify functional activities and symptom severity levels with relatively high accuracy; while is still hard to explore the qualitative level of motion. Of course wearable devices are not free of limitations: as the inability to adequately estimate EE and, above all, the need to reach a common standard of intervention (an issue also related to the wide range of available devices and their different features).

1.3.2 The objectives of the present study

Here are listed the objectives of the study that will be discussed in the future chapters:

- To setup a multi-sensor actigraphic system based on a commercial and professional actigraphic device in order to provide a robust measure of a 24h (all day) motor activity acquisition.
- To define indexes able of quantify epoch-related and global motor activity for each of the body point observed. To define indexes able of a limb prevalence description when two devices are synchronously considered. Furthermore, indexes dependent only on sensor position (i.e., chosen body point), but invariant to sensor orientation.
- To analyze the ability of these indexes to describe a motor picture of motor-healthy subjects.
- To observe the indexes in terms of test-retest reliability.
- To provide information about the acceptability and feasibility of a long-term measurement with multiple wearable devices.

2. Accelerometers

An accelerometer is a device that can measure the acceleration experienced by the corpus to which it is firmly attached: be it a generic object or a human body segment as in the experiment described in this thesis. Operatively speaking, an accelerometer behaves as a **Mass-Spring-Damper system** (**MSD**): when the system experiences an acceleration, a mass (also known as *Proof Mass*), linked to a spring, has a tendency to stay in the same position, because of its inertia; so a displacement between the external case and the internal mass can be detected. This displacement is proportional to the observed acceleration and once converted into an electric signal it is representative of the acceleration experienced by the device; this kind of system is called MSD because, besides the presence of a mass and a spring, a dumper is usually present to help in minimize the mass fluctuations.

Thanks to the technological advances and the possibility of miniaturizing this kind of devices, today, accelerometer-based technology is widely applied in industry and science. This made accelerometers really more common than you can think and detectable in the automotive industry as in the everyday tablets or smartphones, but these are just few examples. Within the last years, the limited costs made this technology spread also in the world of sport and consumer electronics so that it is common to find it into branded sport watches used to monitor speed and distance by the runners wearing them. Lastly, as discussed in the previous chapter, this devices involved also the healthcare and rehabilitation area with professional devices specifically designed.

In **Chapter1** we talked about actigraphy and its possible medical applications, in this chapter and in the paragraphs below there is a more detailed description of an accelerometer functioning and of its features.

2.1 MSD - Analytical description

As said, a second order MSD system perfectly models the general structure of an accelerometer. A system is called a second order system whether the differential equation describing its dynamical response is a second order equation as the one showed in *(2.1)*

$$a_2 \frac{d^2y(t)}{dt^2} + a_1 \frac{dy(t)}{dt} + a_0 y(t) = b_0 x(t) \quad (2.1)$$

where a_0, a_1 and a_2 are generic coefficents, while *y(t)* and *x(t)* are the observed variable and the forcing variable respectively, both time dependent.

Considering the **Figure2.1** showing a MSD-system, it is possible to write a second order equation as the one presented in *(2.2)*.

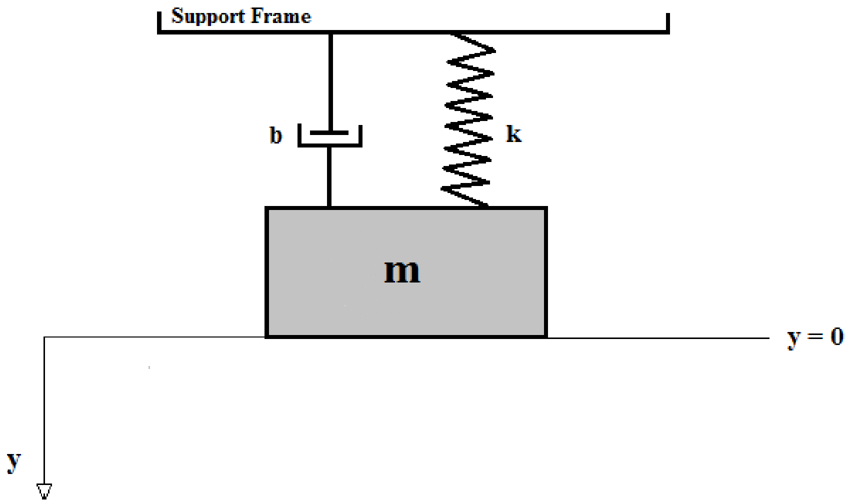

Fig. 2.1 - MSD - system example scheme.

$$m\frac{d^2y(t)}{dt^2} + b\frac{dy(t)}{dt} + ky(t) = ma(t) \quad (2.2)$$

where *y(t)* is the time dependent mass displacement along the y-axis marked in figure, *m* the mass, *k* the spring stiffness, *b* the dumper constant and *a(t)* the acceleration experienced. Dividing all the elements of *(2.2)* by *m* you obtain

$$\frac{d^2y(t)}{dt^2} + \frac{b}{m}\frac{dy(t)}{dt} + \frac{k}{m}y(t) = a(t) \quad (2.3)$$

this equation is usually presented in the form of *(2.4)*, where some typical parameters are highlighted

$$\frac{1}{\omega_n^2}\frac{d^2y(t)}{dt^2} + \frac{2\zeta}{\omega_n}\frac{dy(t)}{dt} + y(t) = a(t) \quad (2.4)$$

These parameters are: the undamped angular frequency $\omega_n = \sqrt{k/m}$ and the dumping ratio $\zeta = b/2\sqrt{km}$; (2.4) is sometimes written in a form that does not highlights the dumping ratio ζ , but the quality factor $Q = \sqrt{km}/b$, so that the relation between ζ and Q results to be $\zeta = 1/2Q$.

Through Laplace's transformation you can obtain the transfer function below, that fully describe the system behavior.

$$\frac{Y(s)}{a(s)} = \frac{1}{s^2 + \frac{b}{m}s + \frac{k}{m}} = \frac{1}{s^2 + \frac{\omega_n}{Q}s + \omega_n^2} \quad (2.5)$$

Y(s) and $a(s)$ are the Laplace's transformed of the displacement y(t) and of the acceleration $a(t)$.

A typical request for accelerometer is a $\zeta = 1/\sqrt{2}$, in this way tha bandwith is maximized and the distortion minimized, this implies the following:

$$\zeta = \frac{1}{\sqrt{2}} \;\Rightarrow\; Q = \frac{\sqrt{2}}{2} \quad (2.6)$$

another element it is worth noting is the accelerometer static sensitivity, computable from *(2.5)* in static condition ($s = 0$); sensitivity S is a device's constant.

$$\frac{x_{static}}{a_{static}} = \frac{m}{k} = \frac{1}{\omega_n^2} \quad \Rightarrow \quad x_{static} = \frac{m}{k} a_{static} \quad (2.7)$$

$$S = \frac{m}{k} \quad (2.8)$$

usually an high sensitivity is wanted, this requires a big mass, but at the same time to respect the request by ζ a small mass is needed, in the same way ω_n determines the bandwidth (a bandwidth that is shorter with a shorter *m*). Furthermore all these features are influenced by the productive process.

2.2 Accelerometers classifications and features

The physical principle described above is the mechanical phenomenon underlying an accelerometer; however, accelerometers can be very different in the way they measure the mass displacement and then convert it to an electrical amount, obviously the different technologies influence the intrinsic static and dynamic characteristics of the device. A classification of accelerometers can be done in different ways, for example, taking into account the kind of application for which they are designed, a typical distinction is the one among *accelerometers designed for static acceleration* and *accelerometers designed for dynamic acceleration*. The former are able to observe constant accelerations as gravity (i.e., 0Hz accelerations in general) having what is called a DC response; these instruments usually do not have a particularly large bandwidth, belong to this category strain gauges-based accelerometers (see description later). The latter are used to measure shocks and vibrations, thus time variant accelerations, thanks to a bandwidth from some Hz to tens of kHz, but without a DC response; a classic example are the piezoelectric accelerometers (see description later).

This simple classification is just one of the many, below there is a list of the principal kind of accelerometer technologies on market, considering the common classification based on the principle of transduction.

- **Extensometer-based accelerometer (strain gauges)**

In this kind of device the mass displacement implies a dimensional variation of some strain gauges. The system, in fact, consists in a strain gauge structure linked to a proof mass and to a base (to witch is linked also the mass). The dimensional variation of the strain gauges, caused by the oscillation of the mass, means a variation in the electrical resistance *(2.9)* and so a variation of the measured voltage in a way proportional to the acceleration experienced.

$$R = \frac{\rho L}{A} \quad (2.9)$$

where ρ [Ωm] is the *electrical resistivity*, L [m] is the *length of the conductor* and A [m^2] is the *cross-sectional area of the conductor*. The resistance variation is found calculating the differential *(2.10)*

$$dR = \frac{\rho L}{A} - \rho A^{-2} L dA + L\frac{d\rho}{A} \quad (2.10)$$

the expression can be rewritten in terms of finite variations and in function of standard mechanical parameters

$$\frac{\Delta R}{R} = \frac{\Delta L}{L} - \frac{\Delta A}{A} + \frac{\Delta \rho}{\rho} \quad (2.11)$$

including the Poisson's ratio μ, which correlates the variation of diameter with the variation of length $\Delta D = -\mu \Delta L / L$, you obtain *(2.12)*.

$$\frac{\Delta R}{R} = (1 + 2\mu)\frac{\Delta L}{L} + \frac{\Delta \rho}{\rho} \quad (2.12)$$

the component $(1 + 2\mu)\Delta L / L$ represents a dimensional effect, while $\Delta\rho/\rho$ represents a piezoresistive effect; so the variation of resistance R depends on dimensional variations as length $(\Delta L / L)$ or area $(2\mu \Delta L / L)$ and on variations of resistivity $\Delta\rho/\rho$.

Strain gauges are typically assembled in a Wheatstone bridge configuration (**Fig.2.2**): this layout is ideal for measure little variations of resistance, furthermore it can compensate the strain gauge sensitivity to temperature (N.B.: in metals and semiconductor materials resistivity is a function of temperature ρ(T)). The strain gauges are also usually assembled in a way that arranges them to be deformed along their axis of greatest sensitivity.

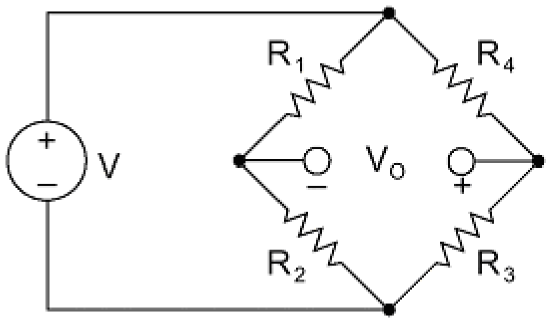

Fig. 2.2 - Wheatstone bridge configuration scheme

The electrical resistances in figure represent the strain gauges, V_0 the outcome voltage consequence of their dimensional variations.

- **Piezoelectric accelerometer**

In this kind of device the acceleration is measured thanks to a piezoelectric crystal, interposed between a mass and a base. Piezoelectric materials are able to produce a charge proportionally to a suffered mechanical deformation *(2.13)* (in this case as consequence of an acceleration), or, vice versa, can deform themselves if subjected to an electric potential. Considering the first option, the mechanical deformation induces a relative displacement of positive and negative charges; so, the internal charges induce surface charges which enable a measure of an electric potential difference between surfaces.

$$q = kF \quad (2.13)$$

The *(2.13)*, with the charge q [C] and the force F [N], is a simplification where k [C/N], the piezoelectric constant, is relative to a single axis of preferential polarization of the crystal. A more accurate description should use a tensor linked with the three spatial dimensions, the axes under strain and the axis from which the charge is measured, but the simplification is not excessive typically existing an axis of maximum sensitivity.

Once the charge is measured, to obtain a voltage is simple if you consult the *(2.14)*, equation that links charge and voltage in a capacitor.

$$V = \frac{q}{C} = \frac{kF}{C} = \frac{kFd}{\varepsilon_0 \varepsilon_r A} \qquad (2.14)$$

These devices, contrary to strain gauges systems, can not measure static acceleration because of the physical principle linking charge q and electrical current I ($I = dq/dt$): being I defined as the first derivative of charge, a constant amount of charge is equal to a null current; in this way results clear that if the proof mass acceleration is constant, the charge derived from the piezoelectric crystal deformation is constant and so null the measure.

Accelerometers are built with piezoelectric crystals sliced and shaped to obtain different characteristics: uniaxial accelerometers with a single crystal sensitive along a unique direction, triaxial accelerometers with multiple uniaxial crystals, triaxial accelerometers with a single multiaxial crystal and so on.

- **Capacitive accelerometer**

In this kind of device the measurement of the acceleration is committed to a capacitor: the mass displacement implies a capacitance variation, as always proportional to the acceleration measured. In particular, the capacitance variation is due to a variation of distance between the capacitor plates as consequence of the *(2.15)*, in the hypothesis of a plane capacitor with parallel plates where C [F] is the capacitance, ε_0 [Fm^{-1}] is the vacuum permittivity, ε_r is the relative permittivity [Fm^{-1}], A [m^2] is the area of overlap of the two plates and *d* [m] is the distance between the plates.

$$C_0 = \varepsilon_0 \varepsilon_r \frac{A}{d} = \varepsilon \frac{A}{d} \quad (2.15)$$

Observing *(2.15)* becomes clear how is possible to vary a capacitance simply, indifferently, changing one of the parameters among ε_r, A or *d*; however, the simplest way to implement, and so the more commonly used, is based on the variation of *d*. Usually the proof mass represents itself one plate of the capacitor while the other one is fixed to the base of the device. Also in this configuration you can imagine a spring and a dumper connected to the mass with the aim to keep suspended the mass-plate avoiding the plates touching themselves and minimize the mass fluctuations, respectively; an example scheme is showed is **Figure2.3**.

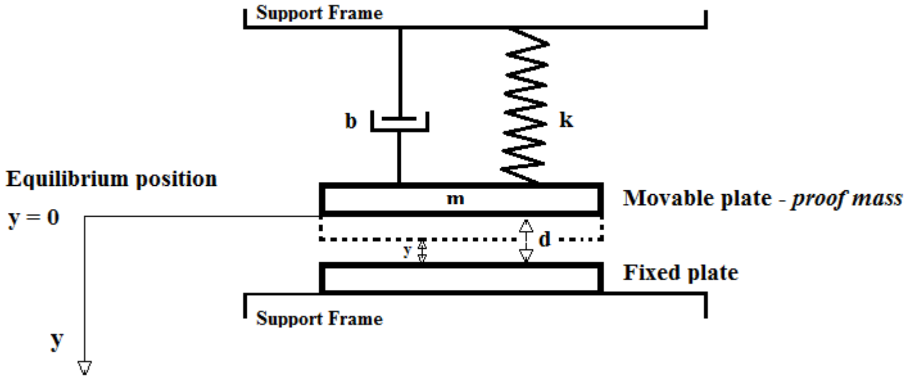

Fig. 2.3 - Capacitive device example scheme.

Capacitive accelerometers appear really good to be realized in form of MEMS, then easy to integrate in all kind of devices. Today, due to the technological developments, **MEMS** (**Micro Electro-Mechanical Systems)** technologies has become very common. MEMS-based devices are easily manufacturable, substantially, although with some modifications, exploiting the industrial production methods of classic electronics: as basic techniques of deposition of material layers, patterning by photolithography or etching to produce the required shapes. Therefore, given a signal of interest, you can implement all the components of a transduction and conditioning units on a silicon chip, in the form of an integrated circuit. The focus point is that MEMS are not to be confused with the simple microelectronics: unlike electronic circuits MEMS have cavities, channels, cantilevers, membranes and so on, thanks to which, in some way, they imitate mechanical parts; moreover, as mentioned above, they allow a real system integration and instead of having a series of external components (e.g., sensors, capacitors, inductors etc.) connected by wire or soldered to a printed circuit board, the MEMS on silicon can be integrated directly with the electronics, towards a concrete miniaturization of existing devices and their new application in different fields. **Figure2.3** is an illustrative example of a MEMS capacitor accelerometer microstructure.

[N.B.: many MEMS are not based on silicon and can be manufactured in glass, polymer or other materials.]

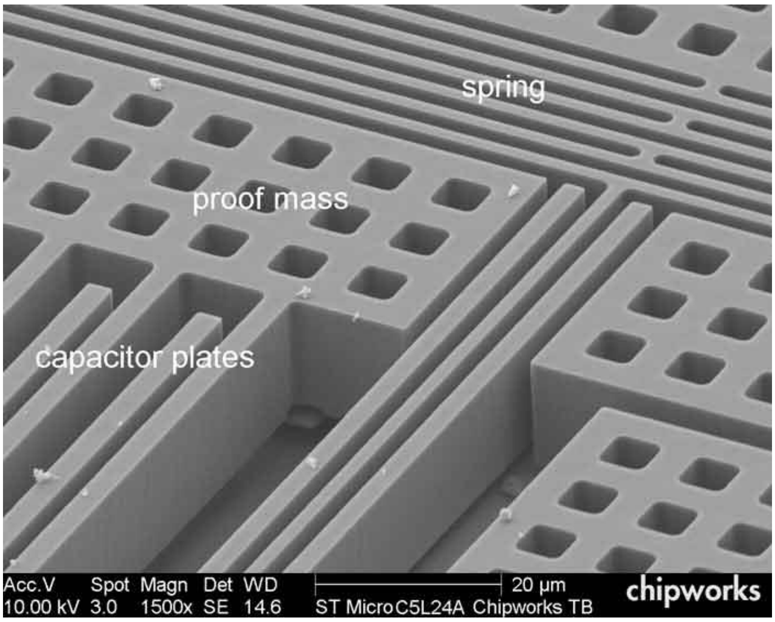

Fig. 2.3 - MEMS capacitor accelerometer structure example.

As the name suggests, MEMS are made up of components between 1 to 100 micrometers [µm], while MEMS devices generally range in size from 20 micrometers [µm] to a millimeter [mm]. **Figure2.3** is an illustrative example of a MEMS capacitor accelerometer microstructure. The devices used in this study are based on MEMS-accelerometers technology.

Below is described the ideal functioning of capacitive MEMS-accelerometers:

A MEMS accelerometer is composed by a proof mass attached to a frame by a springs suspension system, the plates of all the capacitors are composed by the movable plates represented by the proof mass and by stationary outer plates as showed in figure (**Fig.2.5**).

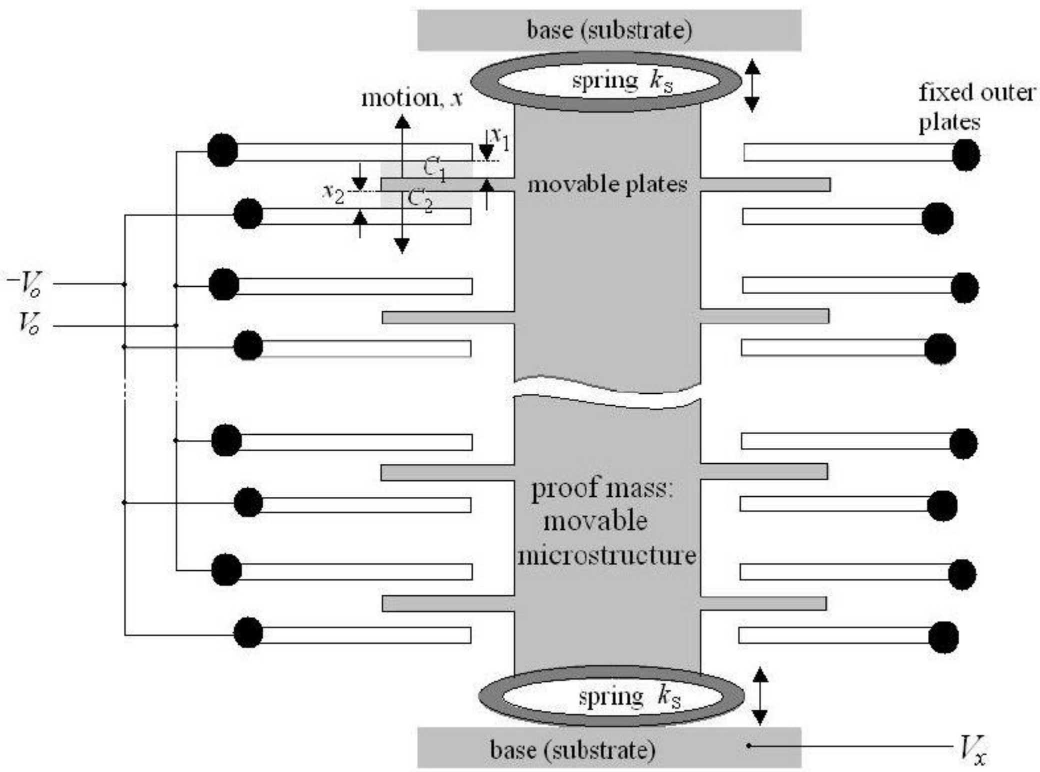

Fig. 2.4 - MEMS - accelerometer basic structure; K_s is the spring stiffness.

The capacitances C_1 and C_2, result of the capacitors represented by the proof mass and the outer plates, are function of the plates distances x_1 and x_2 respectively *(2.16)* as consequence of *(2.15)*; x is the mass displacement due to acceleration.

$$C_1 = \varepsilon\frac{A}{x_1} = \varepsilon\frac{A}{d+x} = C_0 - \Delta C \quad C_2 = \varepsilon\frac{A}{x_2} = \varepsilon\frac{A}{d-x} = C_0 + \Delta C \quad (2.16)$$

in case of null acceleration $x_1 = x_2$ and so are also the capacitances $C_1 = C_2$; while if $x \neq 0$ the difference between C_1 and C_2 is *(2.17)*

$$C_2 - C_1 = 2\Delta C = 2\varepsilon A\frac{x}{d^2 - x^2} \quad (2.17)$$

measuring ΔC you can find the *x* displacement solving the nonlinear algebraic equation derived from the latter equation

$$\Delta C x^2 + \varepsilon A x - \Delta C d^2 = 0 \quad (2.18)$$

in case of small displacement $\Delta C x^2$ is negligible and the solution is *(2.19)*

$$x \approx \frac{d^2}{\varepsilon A}\Delta C = \frac{d}{C_0}\Delta C \quad (2.19)$$

from *(2.19)* becomes clear that the displacement *x* is easily computable being substantially proportional to the capacitances difference ΔC.

It is worth noting that a MEMS-accelerometer is not constituted by a single capacitor, but by a sort of capacitors set as previously showed in figure; considering V_0 the supply voltage, V_x is the output voltage consequence of the mass displacement. Observing a MEMS - accelerometer what can you see is a set of capacitors where the basic system unit is represented by a couple of capacitors as the one described above: when the device experiences no acceleration the capacitances of the two coupled capacitors are equal, while when an acceleration is present they see a complementary variation of C, if C_1 increases C_2 decreases (and vice versa), but their sum remains constant; all the capacitors couple are connected to provide an unique voltage output.

One of the parameters that mostly influences the device skills is d_{max}, namely the distance between the movable plate and the fixed plate, thus the max possible displacement granted to the plate: d_{max} imposes a limit to the max acceleration detectable. It is a feature heavily dependent from the production processes.

2.2.1 Characteristic parameters of an accelerometer

In order to allow a comparison between different available devices, when you are going to choose a specific accelerometer in order to perform an activity, you need a set of quantitative features describing the device's performances; although the first thing to consider is always the kind of technology on which is based the instrument (e.g., strain gauges, piezoelectric etc.), because it defines the macroscopic skills of the accelerometer (e.g., the possibility of a DC response or not). Below there is a brief description of some typical features detectable into an accelerometer datasheet and that you should consult to perform the best choice in relation to the needs:

- **Frequency response or Bandwidth**

This is one of the most important features: to obtain accurate outcomes is absolutely impossible if you choose a device with a bandwidth that does not include the proper frequency of the motion/vibration you are hoping to measure; it is usual that the frequencies specified are also accompanied with a Bode-plot for a better comprehension. Bandwidth information tells the user if the accelerometer can measure slow or static accelerations and also defines the upper frequency limit where the accelerometer will still be accurate.

It is possible that a bandwidth does not include the 0Hz frequency (DC-response), this means that the accelerometer can not acquire constant accelerations like the one determined by gravity or slow vibrations: this feature should be taken into serious consideration in relation with the needs, as already said, for example, a piezoelectric crystal-based accelerometer is typical case of accelerometer without DC-response.

Depending on the application, it is possible to limit the frequency response through the use of filtering systems: naturally, a redefinition of the bandwidth influences the eventual A/D step and the definition of the sampling frequency in accordance with the Nyquist–Shannon sampling theorem.

- **Measurement Range**

This feature does not need particular explanations, as the name suggests the *measurement range* defines the range of acceleration amplitude the accelerometer can measure ensuring a linear output. It is important not to confuse this parameter with the maximum acceleration level the device can tolerate before damaging.

This feature is usually defined as a symmetric interval of ±N [g], where g stands for the standard acceleration due to gravity equals to 9.81 m/s^2.

- **Sensitivity**

The sensitivity or static sensitivity of a device is defined as the ratio between the incremental output amount and the incremental input amount; assuming, in the case of an accelerometer, an acceleration as input and a voltage as output, sensitivity is expressed in [mV/g].

$$Sensitivity = \frac{\Delta V_{out}}{\Delta a_{in}} \qquad (2.20)$$

Sensitivity represents the slope *m* of the line in a Cartesian plane input-output, its value can be constant only in a limited portion of the diagram, due to a drift of the output in case of overly large inputs. The sensitivity that you desire depends on the level of the signal you wish to measure: if you are interested in small vibrations then a higher sensitivity will be desirable, while if you want to measure higher amplitudes for shock events you will need a lower sensitivity.

- **Nonlinearity**

This feature expresses the deviation from linearity defined by the ideal line of behavior described by sensitivity. This feature is usually defined as a percentage of full-scale. MEMS - accelerometers usually have very little values of nonlinearity.

- **Resolution**

This feature is usually given just for device with digital output or systems that incorporate an A/D converter. It is a value in bit (e.g., 12-bit) that allows to derive the minimum amount of detectable acceleration [g] known the measurement range.

An example:

- Measurement range = ±10g.
- Resolution = 12-bit.

Having the system a 12-bit resolution, it has available $2^2 = 4096$ levels of measure, dividing a range of 20g (-10g to +10g) into 4096 you obtain a bin of 0.004g. This means that an acceleration of 0.004g is the minimum acceleration detectable by the considered device.

- **Noise**

Noise or Broadband noise is a name to express the total power of noise RMS (Root Mean Square): it is the square root of the power spectral density of the noise output. Total noise is easily calculated from *(2.21)*.

$$Noise = Noise\ Density * \sqrt{Bandwidth * 1.6} \qquad (2.21)$$

- **Zero-g bias level**

This feature expresses the kind of output you should expect in case of a null input (a null acceleration in our case). Being accelerometers transducers that usually convert the input acceleration into an electric signal, this feature is typically defined in output Volts [V] due to a 0 [g] input acceleration. Variation in temperature, unexpected shocks, noise etc. can modify the zero bias level.

- **Temperature sensitivity**

This feature simply refers to the possible shift the sensitivity of an accelerometers can undergo due to temperature: accelerometers are mechanical systems so temperature impacts the device properties and so its sensitivity. Once are known the possible environmental conditions, temperature sensitivity is an important parameter to take in consideration, possibly avoiding devices really sensitive to temperature (e.g., piezoelectric) when extreme absolute values or variations of it are expected.

In case the use of high temperature sensitive accelerometers is mandatory, it is important to arrange in advance some form of temperature compensation to scale the output accordingly to the offset effect of temperature: an example can be the Wheatstone bridge configuration mentioned before.
This feature is usually defined as a percentage shift per degree Celsius [% / °C].

- **Sampling Rate**

The sampling rate simply defines the range of frequencies [Hz] into which is allowed to choose the sampling frequency. Example: the device can use a sampling frequency from 1Hz to 100Hz, the choice will be due to the need.

- **Cross-axes sensitivity**

This feature expresses the coupling between axes. Assuming a 3-axial device, *cross-axes sensitivity* reveals how sensitive the accelerometer is to orthogonal accelerations in comparison to the acceleration measured by a specific axis of the sensor: in fact, in case of an acceleration along *x*, due to physiological errors resulting from the manufacturing process, is normal to expect variation also along *y* and *z*.
This feature is usually defined as a percentage: ideally it should be 0%.

- **Uniaxial or multi-axial accelerometer**

An accelerometer can be less or more complex in terms of axes of sensitivity. A 3-axial accelerometer is able to measure at the same time accelerations from the three spatial direction (*x*, *y*, *z*), so that it shows the response of the system in the three-dimensional space. Nevertheless, for reason linked to costs or interest in a single axis response, you can also opt for an uniaxial accelerometer, used to monitor a single direction.
It is possible to obtain 3-axial devices combining uniaxial systems, this can be also a commercial solution to build 3-axial accelerometers when a single 3-axial sensor is not used.

2.3 Accelerometers and body movement

In the design phase of a study or experiment is essential to be fully aware of the physical dimensions you need to observe and measure: in fact, amplitude and frequency content are the main parameters that influence the choice and design of the measurement chain. This careful approach is particularly important in biomedical studies were the variables are of biological nature and, for intrinsic reasons, complex. A typical example of an element that distinguishes biomedical quantities, is the presence of variable of small amplitudes, small if compared with typical non-biomedical quantities (e.g., amplitudes of electric variables in electric circuits, amplitudes of pressures in hydraulic circuits); a similar argument can be done also in terms of characteristic frequencies.

The human and biological variables are anything but deterministic, are time-variant also when all the possible parameters are controlled, present an extremely high variability inter- and intra-subject and depend on the state of health: all because of the complex interaction between the many physiological systems involved in a human body. Furthermore, unlike other contexts, many variables are not completely accessible (e.g., cardiac output) and so need to be investigated indirectly, so that rectify the outcomes in the suitable way is mandatory. **Table2.1** shows some examples of physiological variables and their characteristics as range of amplitude and bandwidth .

Tab. 2.1 - Examples of physiological variables and their characteristics.

Parameter or measurement technique	Range of amplitude	Bandwidth [Hz]
Arterial pressure	25-400 mmHg	0-60
ECG	0.5-4 mV	0.01-250
EEG	5-300 μV	0-150
EMG	0.1-5 mV	0-10000

To measure and evaluate the body movements makes no difference: the degrees of freedom of the body segments, the modular amplitudes' range and the different frequencies displayable makes hard an easy description of motor gestures. When choosing an appropriate accelerometer for the assessment of daily physical activity and so the monitoring of human movement, one should consider the specifications of the available electronics as well as the characteristics of human movement which determine the output. In general, frequencies and amplitudes of accelerations involved in human daily activities are relatively low (fractions of g) and possibly the largest accelerations values are expected for activities as locomotion, with peaks in running or jumping.

Considering a principal activity as locomotion, this is what can be observed:

- **Frequency**

During an activity as locomotion, frequencies are generally higher in the vertical than in the medio-lateral or the antero-posterior directions and the frequency spectrum shifts toward higher frequencies from the head to the lower limbs. Walking at natural velocity causes in the upper body accelerations ranged from 0.8–5Hz, whereas the most abrupt occur at the foot (always in vertical direction) during heel strike and sometimes amount up to 60Hz; however, studies demonstrated that in a percentage of cases equivalent almost to the total, the acceleration at feet is concentrated below 15Hz. Higher frequencies are caused by the impact between foot and walking surface and do not directly result from voluntary muscular work [3].

- **Amplitude**

The behavior of amplitudes when walk is observed is similar to what is said for frequencies: during locomotion the higher amplitudes of acceleration are observed in vertical direction and increase continuing from head towards the lower segments. At the tibia, for example, the amplitude of accelerations measured in walking test varies between -1.7 and 3.3g in the vertical direction and between -2.1 and 2.3g in the horizontal directions, while they have maximum and minimum less then |1.0g| when the upper body is observed.

During running were observed absolute vertical peak accelerations ranging from 0.8 to 4.0g at the head, from 0.9 to 5.0g at the low back, and from 3.0 to 12.0g at the ankles [3].

- **Desirable frequency and amplitude ranges**

Considering results as those exposed above, body accelerometers must be able to measure accelerations within the amplitude range of -12 to 12 g and with a bandwidth up to 20Hz in order to assess daily physical activity [3].

Speaking about human movement and actigraphic acquisition, the interest is focused on the kinematics of the body segments on which the accelerometers are positioned. It is hard to perform an ideal measure not only because of the complexity of the motor gesture itself, but because one needs to consider that acquiring the acceleration of a body segment does not mean perform a simple measure of the acceleration of a completely rigid element: a body segment, whether it is an arm, a leg or something else, is composed by a rigid component (i.e., the bone), but also by soft tissues that bring some issues. Because of the presence of tissues, when an accelerometer is positioned on a body segment, the question that arises is *"what am I actually measuring ? the real acceleration of the rigid segment or an amount overly influenced by the soft tissues presence ?"*.

Overall is possible to synthesize in four points the factors that mostly influence the measure:

1. The effective bone acceleration.
2. Gravity.
3. Rotational motions.
4. Issues due to device positioning.

The latter is substantially the only point on which is possible to act. In an ideal world the accelerometer should be fixed on the segment in the more constrained way, for example with screws, in order to move rigidly with it, but this is a method obviously not viable because of invasiveness. The modes and the precision of the fixing is a crucial point and the more the fixing is stable the more the measured acceleration corresponds to the real one. In the experiment described in this thesis the set of accelerometers used has been fixed with watchstraps for the devices positioned on wrists and Velcro® strips for those positioned on waist and sacrum: the volunteers were instructed to fix the device sufficiently tight in order to both not observe devices displacements and be comfortable.

For what has been said a body segment acceleration measured by an accelerometer device is composed as in *(2.22)*

$$a_{tot} = a_{tr} + a_{rt} + a_g \quad (2.22)$$

where a_{tr}, a_{rt}, a_g are respectively the component due to the translation of the segment, rotation and gravity force. In relation to the movement performed, a different combination of these three components is showed.

Accelerometer sensors respond both to intensity and frequency of movement, are more flexible than pedometers that count movements only when a threshold is passed and are surely the best solution when you desire monitoring in free-living condition, but they are not able to quantify movements as a motion analysis laboratory. Moreover, it is worth noting that using simple accelerometers it is not possible to compute the kinematic of movement as is done using an optoelectronic system: accelerometers are substantially used for outside lab acquisitions, with the aim of quantify a total/global movement of limbs and this is possible using stratagems as movement indexes designed to elude issues as those cited before (rotations, translations etc.).

3. MATERIALS AND METHODS

3.1 THE GENEActiv SENSOR

The study presented in this thesis adopted a set of four GENEActiv devices (*Original model*) by Activinsights Ltd [1][11] for the long-lasting monitoring of motor activities in a group of normal subjects; the four instruments were provided by the *Polo Tecnologico* (Biomedical Technology Department) of the *Fondazione Don Gnocchi - IRCCS S. Maria Nascente* based in Milan, in the frame of a collaboration with the Politecnico di Milano.

The *GENEActiv Original* devices (**Fig.3.1**) have the semblance and the dimensions of ordinary wristwatches, even if they do not have the facility to show the time among their features. Thanks to a set of accessories (e.g., elastic bands with Velcro® strips) it is possible to make them wearable not just as watches, but also strapped on ankles, waist, chest.

Fig. 3.1 - A *GENEActiv Original* device and the USB-cradle for the PC interface.

GENEActiv is a wrist-worn triaxial accelerometer which offers up to 0.5Gb raw data storage in an open format for the objective behavioral monitoring within free-living populations and clinical research. This device has been adopted in both small scale studies and large international cohorts of over 10.000 subjects: academic and medical researchers in physical activity, sleep or performance studies; designed for compliance in free-living scenarios it can be worn by everybody from children through to the elderly [4]. Besides the accelerometer sensor used for the assessment of body activity, motion and posture, GENEActiv is also equipped with a thermistor and a photodiode able of measure temperature and light exposure in all environments (these two last features have not been exploited in our experiment).

In **Table3.1** are listed all the key features of *GENEActiv Original* as reported on the handbook and site [11].

Tab. 3.1 - List of all the features and characteristics of a *GENEActiv Original* device.

PHYSICAL PARAMETRS	
Size	43mm x 40mm x 13mm
Weight	16g (without strap)
Main Housing Material	PC/ABS (medical device grade)
Light Guide Material	PC (medical device grade)
Data Contact Material	Gold-plated
Fixings	20mm heavy duty spring bar
Strap	PU resin
Battery type	Rechargeable lithium polymer
ENVIRONMENTAL PROTECTION	
Moisture ingress	Water-resistant to 10mm (IP67 – 1m 24hrs)
Material ingress	Dust tight (IP67)
Operating temperature	5 – 40 °C
Mechanical impact	0.5m drop resistant
MEASUREMENT CAPABILITIES	
Memory	0.5Gb non-volatile
Logging frequencies	Selectable 10-100Hz

Maximum logging periods	45 days @10Hz, 7 days @100Hz
INTERNAL CLOCK	
Type	Quartz Real Time Clock
Frequency	32.7768 kHz
Accuracy	± 20ppm (± 1.7s per day)
ACCELERATION MEASUREMENTS	
Sensor type	MEMS
Range	±8g
Resolution	12 bit (0.0039g)
LIGHT MEASUREMENTS	
Sensor type	Silicon photodiode
Wavelength	400 to 1100 nm
Range	0 – 3000 Lux typical
Resolution	5 Lux typical
Accuracy	± 10% @ 1000 Lux calibration
TEMPERATURE MEASUREMENT	
Sensor type	Linear active thermistor
Wavelength	0 to 60 °C
Range	0.25 °C
Resolution	±1 °C
Accuracy	Every 30s minimum
USB CONNECTION	
Device	USB 2.0 full speed
Charge cradle	Format 4 unit cradle USB 2.0 High Speed
Charge time	90% @ 2 hours; 100% @ 3 hours
Data download time	Max 15 minutes for 4 concurrent units

GENEActiv is a non-consumer validated device [4] intended for expert users. This actigraph uses a MEMS-based triaxial accelerometer that provides the raw acceleration data from the three axes (x, y, z), this avoid any issues or limitations related to some diffuse post-processed proprietary "count units" [4], and allows all kind of manipulations of the acquired data during the data processing.

In this way GENEActiv turns out to be useful for the purposes of our experiment, based on the definition of specifically designed motor indexes and compute summary of the acquired physical activities. Furthermore, in addition of being mildly waterproof, capable of light and temperature measurement, the device possesses all the desirable features for a wearable device as exposed in **Chapter 1.3**: it is easily wearable, portable, light and contained in dimension (as said, it is substantially comparable to a wristwatch), essential characteristics for long-term acquisitions.

About the importance of a wearable non-invasive device capable of not interfering in the execution of everyday activities, Huberty et al. [14] studied the feasibility (i.e., acceptability, demand) of three widely used wearable sensors, among which also appears GENEActiv. In terms of comparisons between wearable sensors and satisfaction survey responses GENEActiv was acknowledged of being "*easy to wear*" and "*comfortable*" (also during sleep) by participants; the only real drawback, in accordance with the subjects of the study by Huberty, is that the device, unlike other commercial accelerometers, does not act like a real watch and this can be disappointing in people wearing it, mostly whether both wrists are involved in the study and a watch is not wearable in any way. In the conclusions chapter (**Chapter 5**) will be discussed the results of acceptability of GENEActiv in relation to the satisfaction questionnaire filled by the participant for this experiment.

Moreover one of the features of GENEActiv is the possibility to set up a future *"starting time"* with the precision of a minute; this allows to configure the four devices, deliver them to the participants and make them all start at the same time. This feature is fundamental to the aims of the present study which requires a synchronized recording from different sensors.

3.2 SUBJECTS

The study involved 28 subjects (14 men and 14 women) recruited among family, friends and acquaintances of the experimenter. There were no particular requests to be admitted into the group, the only one, besides the willingness to participate, was not to be carrier of motor disorders or chronic disabilities .

Although the experiment aims to reach a preliminary picture of variability among healthy people monitored by actigraphs (on the basis of the motor indexes here developed and used), no discrimination was made to ensure into the group specific amounts of specific features (e.g., handedness, age etc.) as sometimes happens [23][24]. Each choice of a participant was made randomly in accordance with the willingness of the people contacted. The present study is part of a wider study involving also patients which has been approved by the Ethical Committee of the Fondazione Don Carlo Gnocchi, Milano. Therefore the informed consent was submitted to potential participants. Those who agreed to participate (all contacted individuals agreed) signed the form and were assigned a unique code that make him/her (and his/her data) completely anonymous; from the unique anonymous code it is possible to extrapolate only age and sex of the subject.

The **Table3.2** below is a summary of the number, sex and age characteristics of the participants..

Tab. 3.2 - Number, sex and age characteristics of the participants.

SEX	#N of subjects	MEAN AGE [years]	AGE RANGE [years]	MEAN BMI [Kg/m^2]	BMI RANGE [Kg/m^2]
Male	14	34	[18 ; 56]	22.5	[17.7 ; 26.6]
Female	14	40	[20 ; 58]	20.6	[16.1 ; 25.3]
All	28	37	[18 ; 58]	21.7	[16.1 ; 26.6]

All the participants were asked to fill out some questionnaires in order to record demographic data, habits and perception of the experience, in particular:

- A questionnaire about personal and demographic data (e.g., name, surname, age, education, occupation etc.).
- A questionnaire about lifestyle in ordinary days (e.g., time spent sitting, practice sport, daily transfer by transports or not etc.).
- A questionnaire about handedness in the form of an adapted Edinburgh Handedness Inventory Test (Oldfield's Test) [22].

- A timestamped diary of the activities performed during the monitoring day.
- A questionnaire about the experience and acceptance of the actigraphs.

From all these documents many informations which describe the group were extracted: here are highlighted the education school time, ranging between 8 to 18 years, and the participants' occupations, which include 10 students, 9 office workers, 4 warehousemen, 2 pharmacists, 1 sales agent, 1 riding instructor, 1 cook.

Table3.3 summarizes the participants characteristics in terms of *"Lifestyle"*, the data were extracted from the Lifestyle-questionnaire. Some notes: the *"Practice sport"* percentage is computed on all participants and expresses the percentage of subjects who consistently practice sport during the week; the column *"Average training frequency"* refers just to those who actually practice sport and not to all subjects (e.g., between the men who practice sport the average training frequency is 2.7 day per week).

Tab. 2.3 - Lifestyle characteristics of the participants.

	Practice sport [%]	**Average training frequency [day/week]**	**Moving by public transports - average [min/day]**	**Moving by foot/bike - average [min/day]**	**Average time spent sitting [h/day]**
Male	78.6%	2.7	92	38	9.0
Female	57.1%	3.0	51	31	7.5
All	67.9%	2.8	72	35	8.0

All the acquisitions took place on a generic week day excluded weekends (Monday to Friday). The reason is related to the objective of establishing a set of normative values: to include the weekends could have been a source of distortion considering that many people in the weekends are inclined to relax or practice activities significantly different from what can be observed during a common working day. Nonetheless it would be an interesting object of future studies to correlate the activity of an individual during the working week to the activities during days off.

Five subjects (2 men and 3 women with age ranged from 23 to 58 years, mean 43) repeated the monitoring after the first assessment in order to assess test-retest reliability of the indexes. When possible, in relation to the availability of the participants, the retest session took place in the same day of the week of the first acquisition in order to minimize any external confounding factor, otherwise a comparable day was chosen.

3.3 SENSORS POSITIONING

The strong miniaturization of technology and the restrained costs allow for many different setups using multiple and non-invasive sensors. The present study aims to monitor the movement variability in healthy subject during a 24h registration with the four devices supplied. Having available just four sensors, at first, the choice has been oriented to the monitoring of the limbs (upper and lower), but then we revisited it introducing a common-mode signal represented by the signal from the pelvis (sacrum), assumed to be expression of the body center of mass [8][13], and removing the sensor on one lower limb.

The definitive configuration is showed in **Figure3.2**: it monitors the upper limbs at the level of the wrists, a third sensors is located on the pelvis, strapped to an elastic waist-belt at the level of the sacrum and a last fourth sensor on one of the lower limbs at the level of the ankle (the lower limb chosen depends on the subject's handedness (Oldfield's test outcome). The availability of only four devices implied not to consider one limb sensor, to discard one lower limb from the monitoring seemed an obvious choice in order to favor a monitoring of the expected higher variability of upper limbs during the 24h.

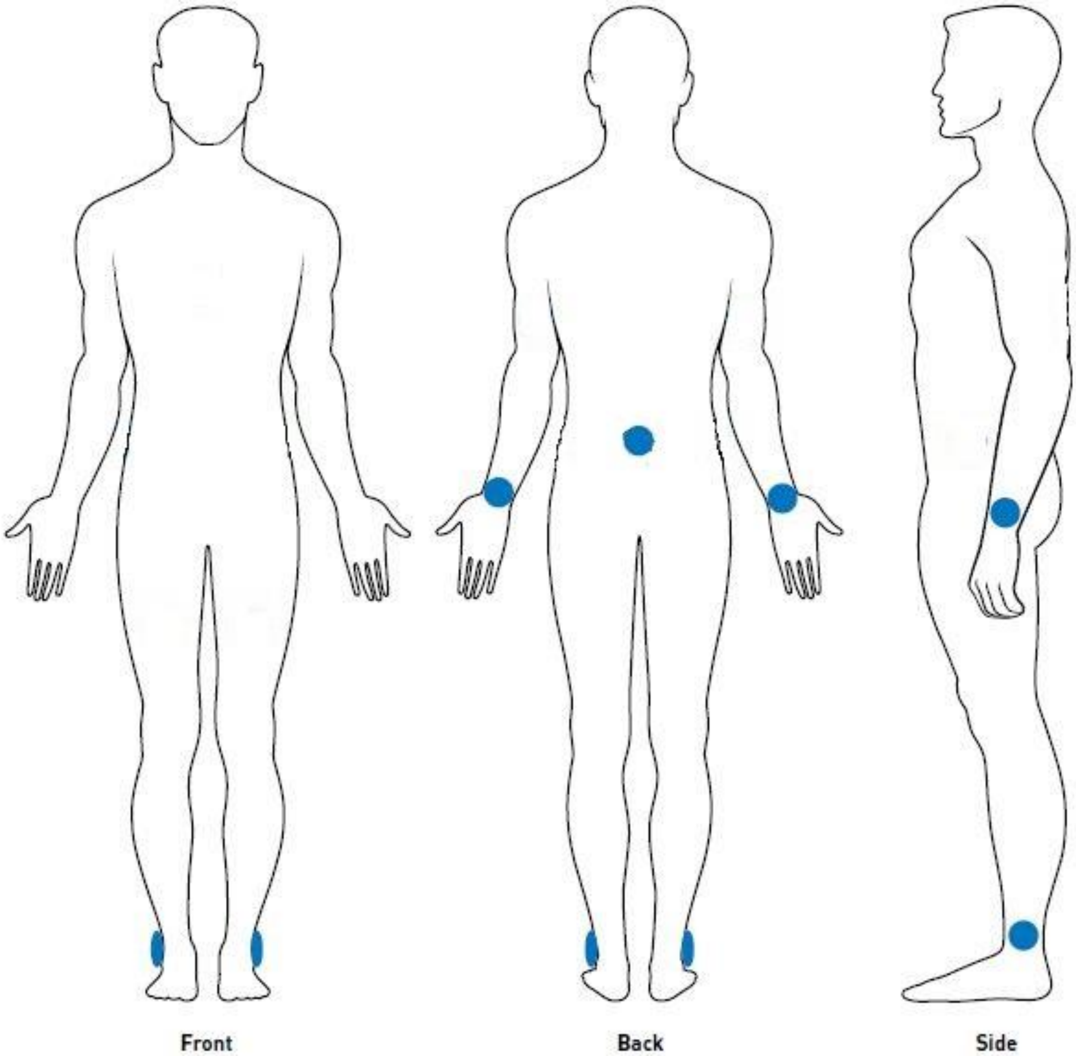

Fig. 3.2 - The configuration of the 4 devices during the acquisition;
the accelerometers on the ankles must be interpreted as alternative.

3.4 ACTIVITY INDEXES

The experiment consisted in long-lasting recordings (24h) of daily motor activities. The continuous measurement (sampling frequency was 50 Hz) of acceleration components were further elaborated in order to extract and compute scalar performance indexes for each considered time epoch. In the present study the duration of the single epoch was fixed at 1 minute [23].

Accelerometric acquisitions usually bring with them issues linked to the accelerometers nature itself: when using an uniaxial device, for example, it is mandatory to strictly fulfill all requirements about the sensor orientation, otherwise the gravitation component may overcome and mask the analyzed phenomenon. This aspect is particularly critic if the participant himself, possibly with motor disorders, has to dress the device, since sensor positioning errors are more likely to happen for not expert operators. Today triaxial accelerometers as GENEActiv are more common than in the past and allow a more flexible positioning given that adopted indexes invariant to sensor orientation; in particular the present study involves indexes designed to quantify motor activity depending only on the sensor position but not on the sensor orientation.

The indexes used were defined, and already adopted, by the Polo Tecnologico of the IRCCS "S. Maria Nascente" in a previous study [23] which this one could be considered a sort of prosecution.

3.4.1 Epoch-related Motor Activity index MA_e and 24h average MA_{24h}

Given $\boldsymbol{a_{i,j,e}}$ the **j-th** acceleration sample (out of n total samples) related to the **i-th** spatial component (x, y, z) of the epoch **e**, we can compute the modulus of this j-th sample as follows:

$$a_{j,e} = \sqrt{a_{x,j,e}^2 + a_{y,j,e}^2 + a_{z,j,e}^2} \quad (3.1)$$

in this way the mean of the modulus time series is

$$\bar{a}_e = \frac{\sum_{j=1}^{n} a_{j,e}}{n} \quad (3.2)$$

so $\bar{a}_e$ represents the mean modulus of acceleration for an epoch **e** constituted by j samples; $\bar{a}_e$ does not represent the final index adopted, but it is already an amount independent from the sensor orientation as proposed.

The definition of the motor index is completed as showed in *(3.3)*, where the index is defined, always just for the considered epoch, as the standard deviation of the modulus time series

$$\boldsymbol{MA_e} = \sqrt{\frac{\sum_{j=1}^{n}(a_{j,e} - \boldsymbol{m}a_e)^2}{n-1}} \quad (3.3)$$

or equivalently

$$\boldsymbol{MA_e} = \sqrt{\frac{\sum_{j=1}^{n} a_{j,e}^2 - \frac{1}{n}\sum_{j=1}^{n} a_{j,e}}{n-1}} \quad (3.4)$$

extending the computation to the overall acquisition we can obtain an $\mathbf{MA_{24h}}$ index as an average on the $\mathbf{N_e}$ epochs that constitute the whole registration (e.g., in a 24h acquisition of 1-minute epochs you have N_e = 1440 epochs). The chosen acceleration measurement unit for $\mathbf{MA_e}$ and $\mathbf{MA_{24h}}$ is the thousandth of the gravity acceleration g (1mg = $9.806 \cdot 10^{-3}$ [m/s^2]).

3.4.2 Activity Ratio index AR_{24h}

The **Activity Ratio AR_{24h}** is a second index designed to quantify the unbalance between activities recorded in two body points

Given two synchronized actigraphic recordings, the MA_e profiles at both wrists for example, herewith referred to as $MA_{R,e}$ and $MA_{L,e}$, can be scatterplotted with $MA_{R,e}$ on x-axis and $MA_{L,e}$ on y-axis. Considering the bisection line of the first and third quadrant the data points of the plot (coupled values ($MA_{R,e}$; $MA_{L,e}$)) in the inferior triangular area of the first quadrant mark epochs in which the motor activity is higher for $MA_{R,e}$, vice versa for the superior triangular area where a point stands for an higher activity of $MA_{L,e}$.

Now it is assumed that the geometrical entity able to quantify the searched activity ratio is the best-fitting line passing through the axes origin and minimizing the sum of squares residual [9]; such line, computationally, corresponds to the first eigenvector as obtained by a singular value decomposition in a Principal Component Analysis (PCA).

AR_{24h} is defined as follows:

$$AR24h\ (a, b) = 100 * \frac{45° - \alpha}{45°}$$

the angle α (expressed in arc degree °) corresponds to the angle formed between the bisection line of the first and third quadrant and the best-fitting line described before.

The terms ***a*** and ***b*** in the definition refer to the two actigraphs whose MA_e were considered: in this example they are, respectively, the **$MA_{R,e}$** and **$MA_{L,e}$** mentioned before; the use of two generic ***a*** and ***b*** elements highlights that the index can be computed for any possible couple of two actigraphic registrations as ankle vs wrist, wrist vs sacrum etc., and not only for upper extremities.

This Activity Ratio AR_{24h} index, as it has been defined, has a range of possible values from +100% to -100%: a generic positive value stands for a prevalence of the ***a*** component (+100% is an exclusive *a* activity against a null *b* activity for the whole duration of the acquisition) , while a negative value stands for the prevalence of ***b***; in this way an AR_{24h} null value corresponds to a perfect symmetry between *a* and *b* for the considered time period. In the particular case of the sensors being placed on symmetrical locations (e.g. both wrists) the AR index represents an asymmetry index where motor symmetry means that the two symmetrical points have a balanced activity throughout the duration of the monitoring (and not for each epoch).

3.5 THE ACQUISITION

In order to perform an acquisition, each GENEActiv device needs to be configured within the proprietary software *GENEActiv PC Software* (ver. 2.9). The software allows us to choose from different settings concerning *measurement frequency*, *measurement period*, *recording start mode*, *body location of the device* and so on, **Figure3.3** and **Figure3.4** show two screenshots**.** The interface with the software is possible thanks to a USB-cradle on which is possible to connect up to four device at the same time.

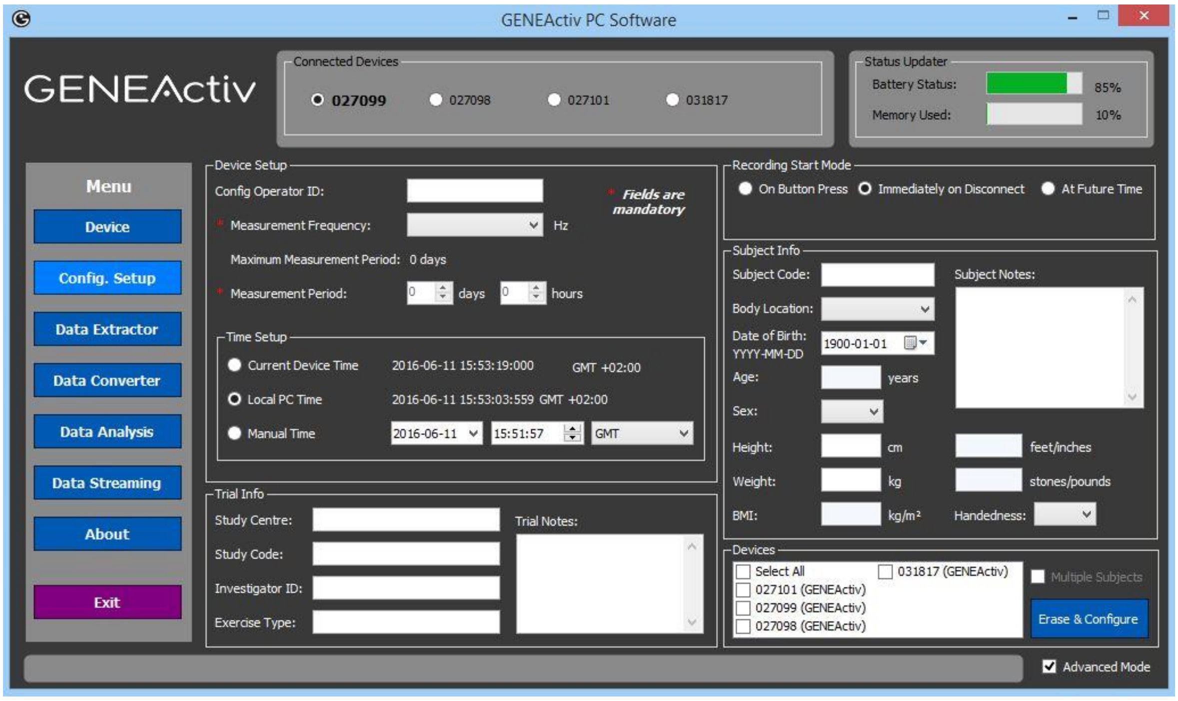

Fig. 3.3 - Screenshot from *GENEActiv PC Software* (ver. 2.9).

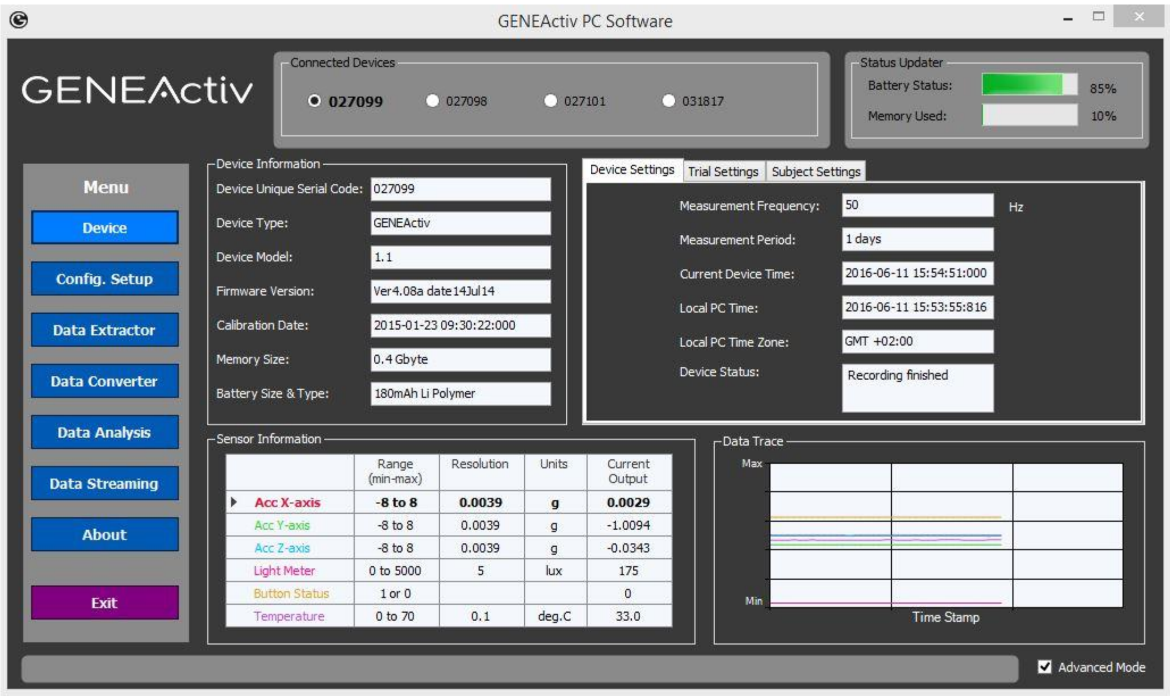

Fig. 3.4 - Screenshot from *GENEActiv PC Software* (ver. 2.9).

The software allows also to label an acquisition with many personal values as age, sex, height, weight, BMI and handedness. For the purposes of a simple description of the acquisition methods the setting variables of interest are two, these values were common for all the subjects:

- **Measurement period**: 1 day (24 hours).
- **Measurement (sampling) frequency**: 50 Hz.

The measurement period has been discussed previously, the around-the-clock registration wants to acquire a global motor activity during a common working day; even if, in power, the GENEActiv device is capable of days-long acquisitions (up to 14 days with a 50Hz sampling frequency), this feature was not of interest both for a matter of timing (the time duration of the whole experiment would have been significantly increased) that because of the greater effort required to the participants in case of multiple days of acquisition.

For what concerns the measurement frequency, the maximum sampling frequency for GENEActiv is 100Hz: in our experiment 50Hz was chosen for different reasons. Of course at first the choice moved toward the respect of the Nyquist–Shannon sampling theorem, in accordance with the frequencies expected for a human body and limbs movement.

Then the final choice was made taking into account our computational limit: the computer used for the data elaboration could not manage with raw acceleration data sampled at frequencies greater than 50Hz during the calculation of the indexes, in fact the amount of data is really big if you think to acquire at 100Hz 24h of activity (about 8640Ksamples, against the 4320Ksamples of a 50Hz acquisition).

Once completed the acquisition, the sensors are connected to the PC by placing them into the cradle and the raw data are downloaded by *GENEActiv PC Software*: the download from each device produces a text file (strangely enough, with extension ".bin") containing all the x-y-z accelerations data and all the collateral information such as those provided in the configuration phase (e.g., sampling frequency, start time, trial info, subject info, calibration info). *GENEActiv PC Software* presents also tools to convert the output file to other file formats and to simply analyze the data, but none of this features was used in this experiment since a routine for reading bin files has been written.

Once the devices were set up they were delivered to the subject. During the first meeting the subject received also the informed consent form to sign, the personal data questionnaire, the Edinburgh Handedness Inventory Test questionnaire, the lifestyle questionnaire and the daily diary, then was taught how to dress the devices and fill the documents; so all the files, except the daily diary to fill with the activities done during the experiment, were collected. About twenty-four hours later, in a second meeting, the devices were withdrawn and the subject was asked to fill the last questionnaire about the experience with the actigraphs in terms of acceptability.

Here the simple wearing instructions provided to the participants:

- Position of each actigraph.
- The actigraphs must be donned for 24h from the agreed start time, even during sleep.
- The actigraphs must be removed during extended water activities (e.g., a shower, but not during hand-washing).
- Wanting to design a collection of motion data based on indexes independent from the accelerometers orientation, no instruction or hint about it was give to the participants.

The choice to remove the devices during extended water activities (although they are defined mildly waterproof by the producer) is a simple precaution in order to avoid a possible cause of failure.

In order to avoid any possible bias due to offsets between actigraphs (the devices have been calibrated by the producer and only the producer can re-calibrate them), the donned actigraphs of each registration session were randomly selected from the available set: in this way, during a generic session, each of the accelerometers could have been worn on a wrists, on an ankle or on the waist without preferences.

3.6 DATA PROCESSING

Once the raw data are downloaded from the devices in the form of the *.bin* files they need to be processed in order to extract the movement and asymmetry indexes described before; all the readings and processings of data were done using MATLAB codes written for the purpose.

The MATLAB codes not only provide the MA_{24h} and the AR_{24h} indexes (a complete list of variables computed for each subject can be seen in the results chapter, **Chapter4**), but also give as output two kind of graphical plots:

- **MA_{24h} time profile plots** over the 24h from the start time of acquisition till the end time of it, **Figure3.5**. In particular 1) MA24h(UR) vs MA24h(UL),
  2) MA24h(UR) vs MA24h(S), 3) MA24h(UL) vs MA24h(S),
  4) MA24h(LR) vs MA24h(S).
- **Scatterplots of the MA_e** indexes showing graphically the amount of the relative AR24h (e.g., plotting MA_e(UR) v MA_e(UL) we see represented AR24h(UR,UL)), **Figure3.6**. In particular 1) AR24h(UR,UL), 2) AR24h(LR,UR), 3) AR24h(UR,S), 4) AR24h(UL,S), 5) AR24h(LR,S).

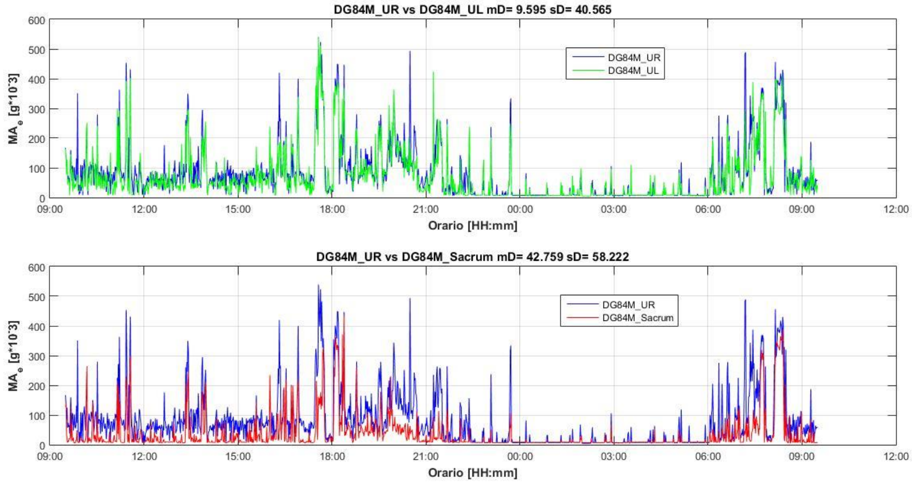

Fig. 3.5 - Examples of MA_{24h} profiles.

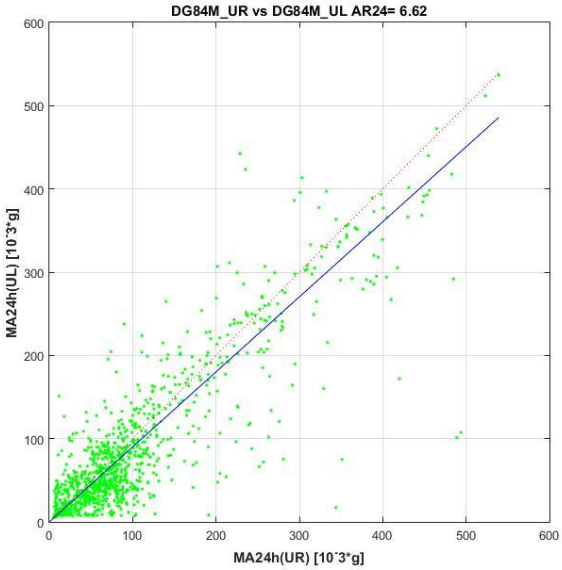

Fig. 3.6 - AR24h(UR,UL) graphic representation; AR24h(UR,UL) =6.62%.

All the indexes values were collected into a spreadsheet used for the statistical processing: to compute descriptive statistics, statistical test and the summary figures showed in the results chapter were used both Microsoft Excel and StatSoft Inc. STATISTICA.

As it will be showed in **Chapter4** the data processing was done at first for the whole lasting 24h registrations, then for all subject has been produced also a results spreadsheet for a reduced fifteen hours (**15h)** time span which excluded night time. The aim of this period contraction is to remove the night sleep phase: in particular, for all subjects, without discrimination, avoiding to obtain registrations of too different durations, all data from 21:00pm-06:00am has been removed following the procedure described in Rabuffetti [23].

4. RESULTS

The following paragraphs report the outcomes of the experiment, each paragraph is specifically focused on one type of the variables computed from the data. This chapter is dedicated to a simple presentation of results, any comment or question will be discussed in the dedicated chapter (**Chapter5**); anyway in the beginning of each paragraphs are presented some questions we wish to answer in the discussions.

4.1 MA_{24h} : Normative Values of Motor Activity Indexes

Some question we wish to answer:

- ✓ *Can the MA_{24h} indexes describe the global motor activity of the limbs, and their relationships, with a certain coherence?*
- ✓ *Are the indexes related to waist (i.e., center of mass) and lower limb expression of locomotion and physical activity?*
- ✓ *In healthy subjects, do the upper limbs show significant difference, according to handedness, in the average motor activity?*
- ✓ *Do MA_{24h} show differences between sex?*
- ✓ *Do MA_{24h} show a relationship with age? In particular, is it reasonable to expect an age-related motor activity reduction?*
- ✓ *What is observed when the subjects are grouped according their occupations?*

The 24h monitorings of the 28 subjects with the four GENEActiv setup provided (excluding the cases in which was impossible to compute the indexes due to measurement errors) four **Motor Activity** (MA_{24h}) indexes for each participant; they are differentiated as follows:

- **MA24h(UR)**: it is the MA24h index for the Upper Right (UR) limb, so it is referred to the device positioned on the right wrist.
- **MA24h(UL)**: it is the MA24h index for the Upper Left (UL) limb, so it is referred to the device positioned on the left wrist.
- **MA24h(S)**: it is the MA24h index for the Sacrum (S), so it is referred to the device positioned on the sacrum.

- **MA24h(LR)**: it is the MA24h index for the Lower Right (LR) limb, so it is referred to the device positioned on the right ankle.

[A MA24h(LL) referred to the left ankle doesn't exist because all the participants evidenced a right handedness, so no person worn a device on the left ankle during the experiment].

As it has already been indicated in Material and Methods (**Chapter3.3**), the unit of measurement for the MA_{24h} indexes is [10^{-3}g], where g stands for the standard acceleration due to gravity (9.81 m/s^2); we want also to remember that for each MA_{24h} index, which is a mean of the overall registration, exist 1440 punctual MA_e values corresponding to each of the 1440 1-minute epochs of a 24h acquisition.

The following **Table4.1** is a summary of descriptive statistics for these indexes of movement, while **Figure4.1** is a comparative boxplot..

Tab. 3.1 - Descriptive statistics for the MA_{24h} indexes.

INDEX	#N of subjects computed	MEAN [10^{-3}g]	St. Dev. [10^{-3}g]	MAX [10^{-3}g]	MIN [10^{-3}g]
MA24h(UR)	28	80.8	27.5	149.3	39.0
MA24h(UL)	26	71.9	25.5	141.5	35.4
MA24h(S)	27	35.9	17.1	94.4	13.9
MA24h(LR)	27	84.6	38.2	174.4	29.3

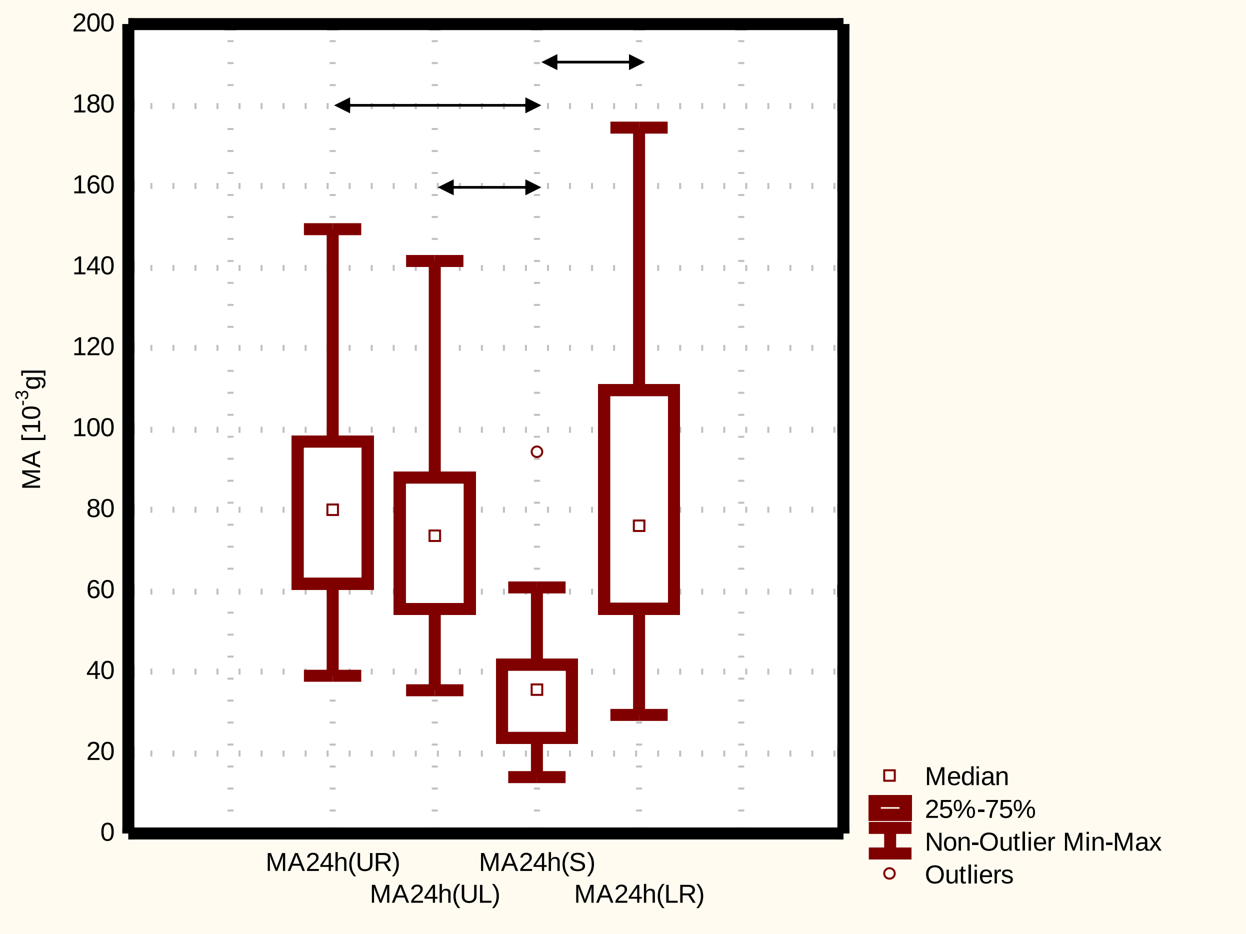

Fig. 4.1 - MA$_{24h}$ indexes comparative boxplot.

A t-test for independent samples ($\alpha = 0.05$) on the means has been performed among the variables, the comparisons show significant differences ($p < 0.001$) between indexes only in the cases in which is involved MA24h(S), see **Table4.2**.

Tab. 4.2 - t-test results for MA$_{24h}$ indexes.

INDEXES	p-value
MA24h(UR)vMA24h(UL)	0.225
MA24h(UR)vMA24h(S)	0.000
MA24h(UR)vMA24h(LR)	0.671
MA24h(UL)vMA24h(S)	0.000
MA24h(LR)vMA24h(S)	0.000

If the variable are grouped by sex **Figure4.2** is the corresponding box-plot.

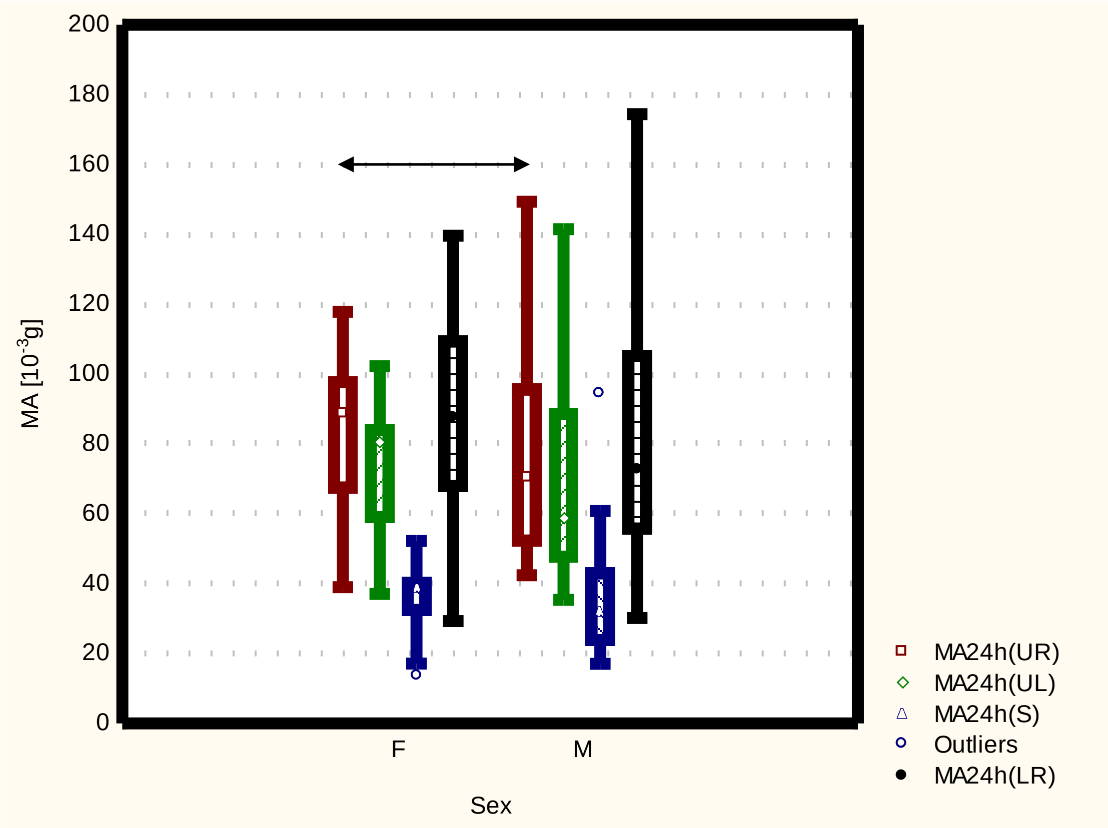

Fig. 4.2 - MA_{24h} indexes grouped by sex, comparative boxplot.

When the indexes are grouped by sex the t-test ($\alpha = 0.05$) on the means shows a significant value ($p = 0.026$) just in the comparison between male-MA24h(UR) and female-MA24h(UR).

As we can expect in subjects not affected by motor impairments, there is an high linear relationship ($0.91 < r < 0.96$; $p < 0.001$) between all the four body points to which the MA_{24h} indexes refer: exists a sort of coherence in movements. The **Figure4.3**, **Figure4.4** and **Figure4.5** show some scatterplots: all the extremities (UR, UL, LR) are linearly related to the movement of the center of mass (approximated by S), at the same time we can observe an high relationship between the two upper limbs (UR,UL) and the ipsilateral upper and lower limb (UR, LR) ($r = 0.96$ and $r = 0.91$, respectively; $p < 0.001$).

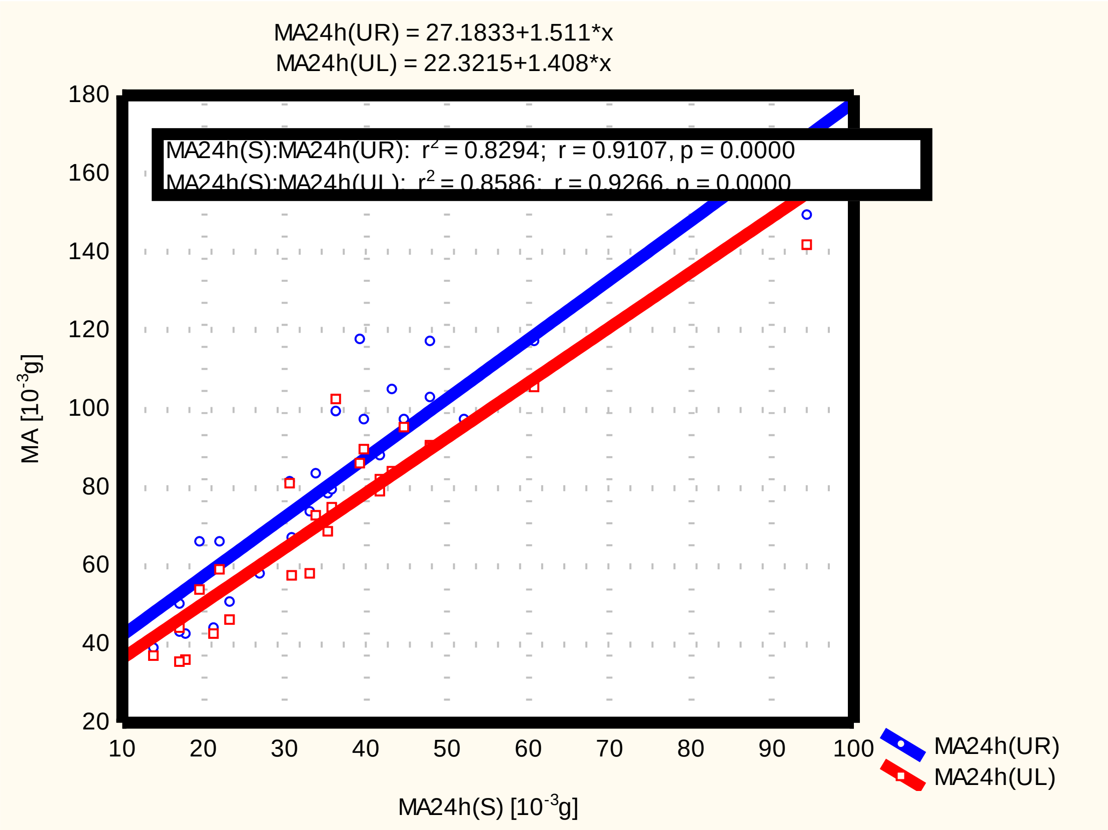

Fig. 4.3 - MA24h(UR) and MA24h(UL) against MA24h(S).

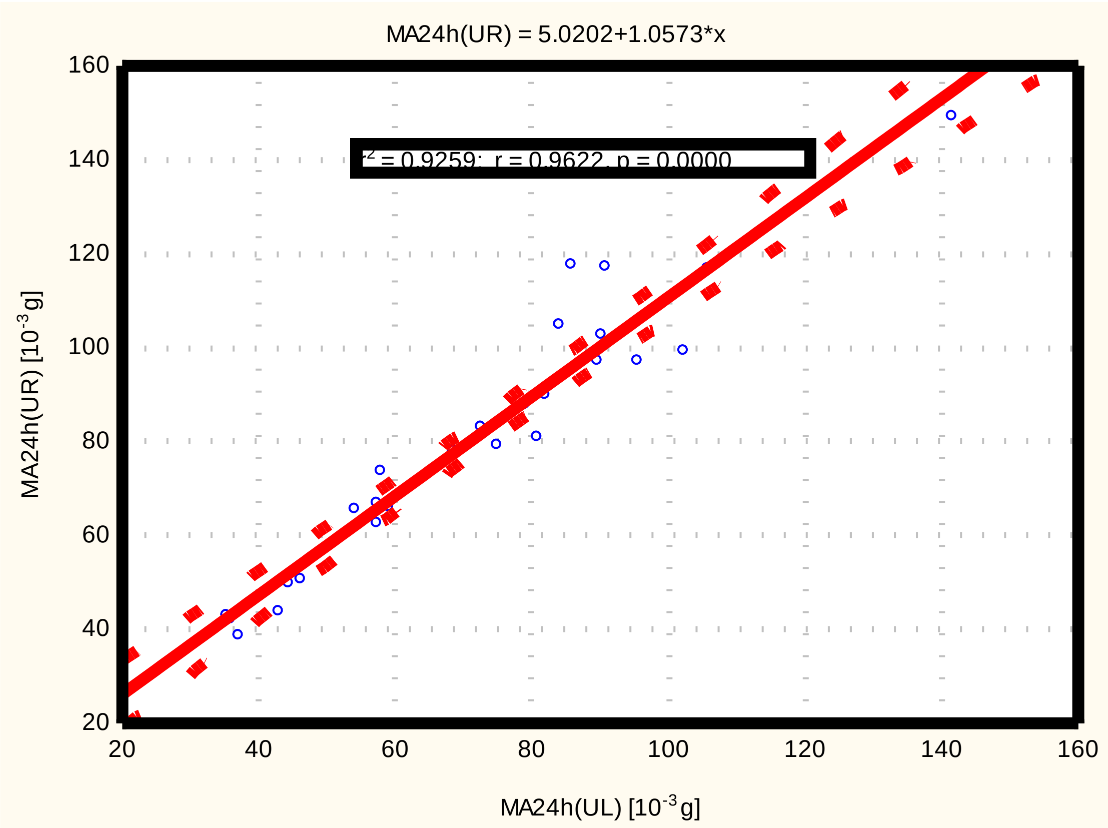

Fig. 4.4 - MA24h(UR) against MA24h(UL.)

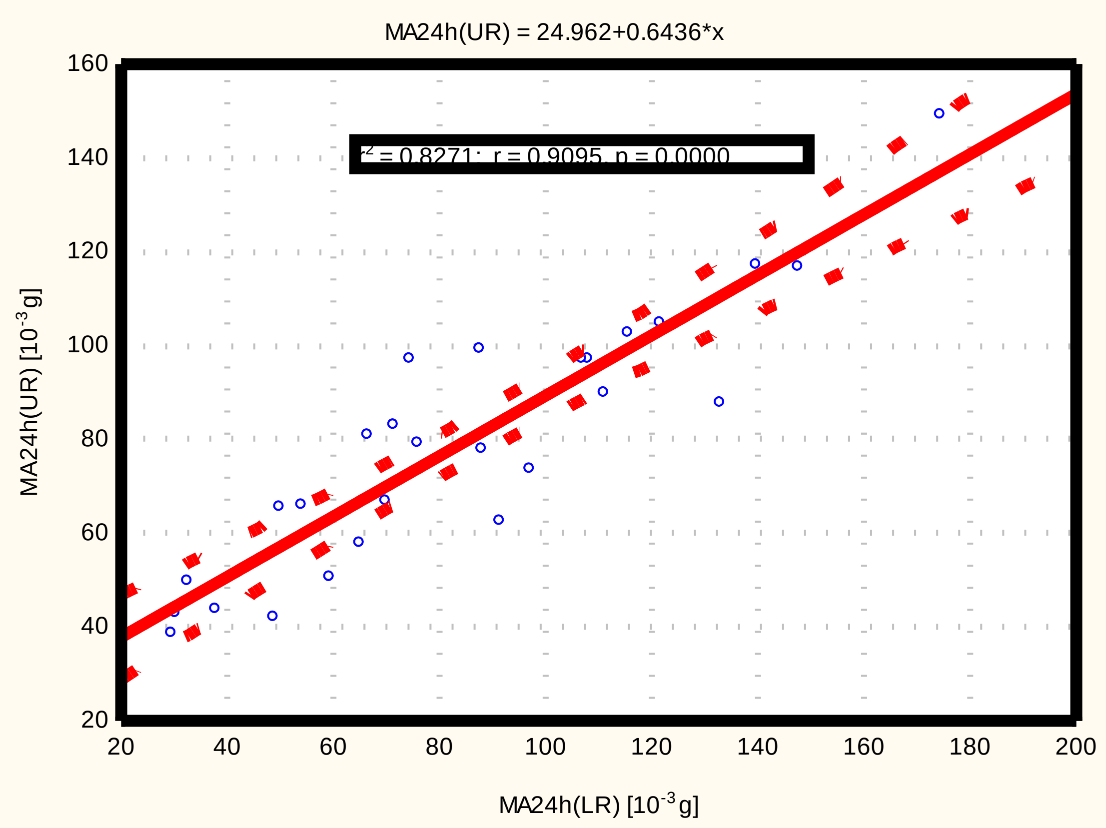

Fig. 4.5 - MA24h(UR) against MA24h(LR).

The **Figure4.6**, **Figure4.7** and **Figure4.8** below let to investigate a possible relationship between MA24h(S) and parameters as BMI (Body Mass Index), age and aPA (approximate Physical Activity per week, in hours) a value independently provided by participants and their subjective perception. In these comparisons MA24h(S) has been the chosen index between the four possible MA_{24h} because it should be the one that best represents the global motor activity of a subject, being approximation of the center of mass displacement.

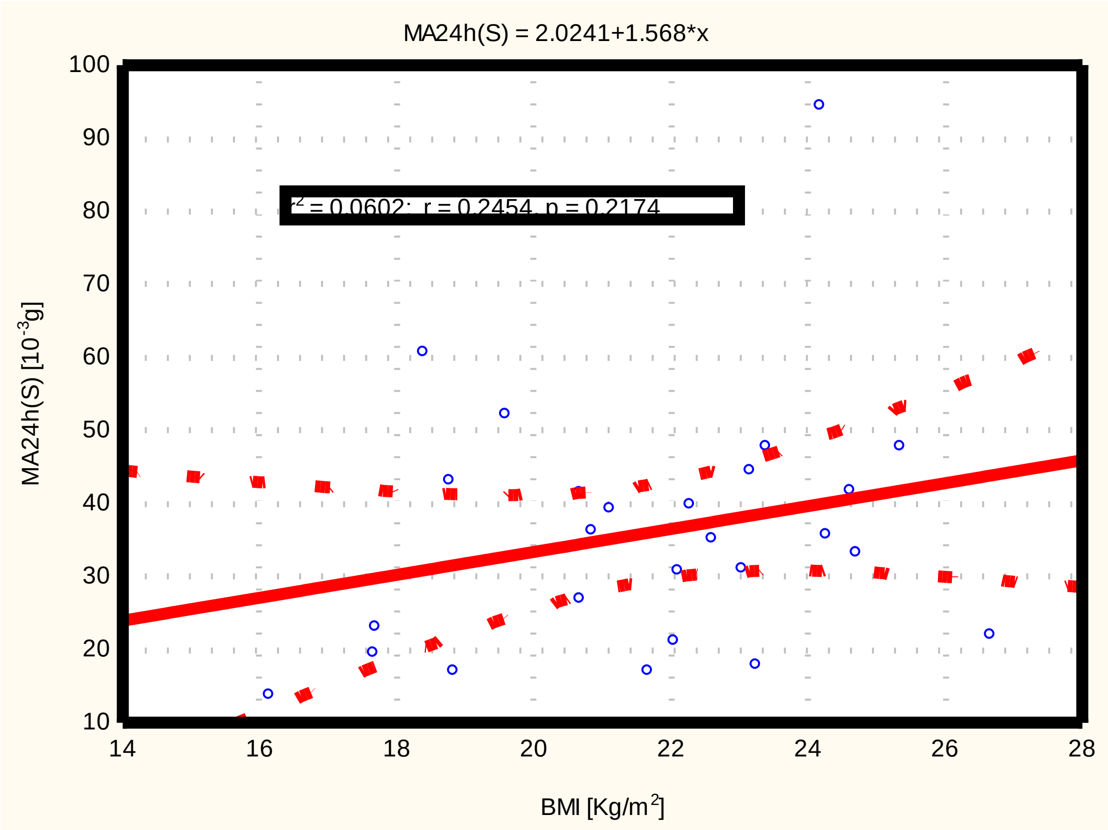

Fig. 4.6 - MA24h(S) against BMI.

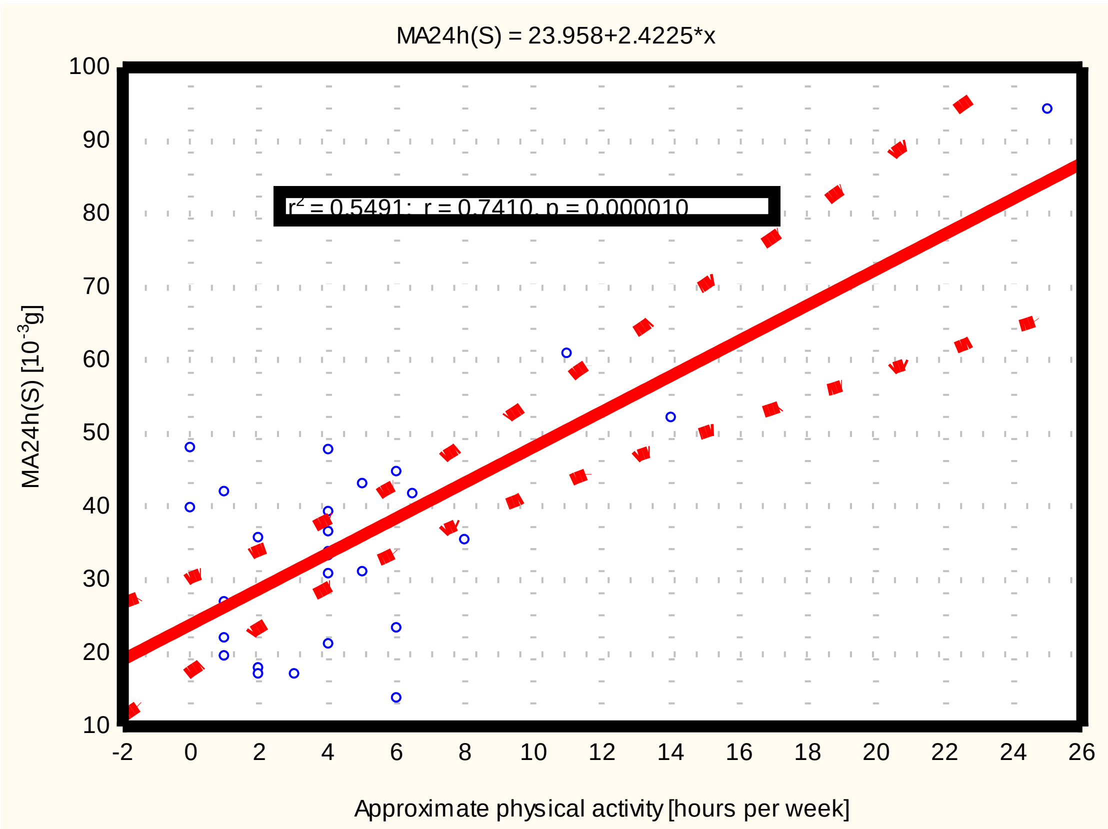

Fig. 4.7 - MA24h(S) against aPA.

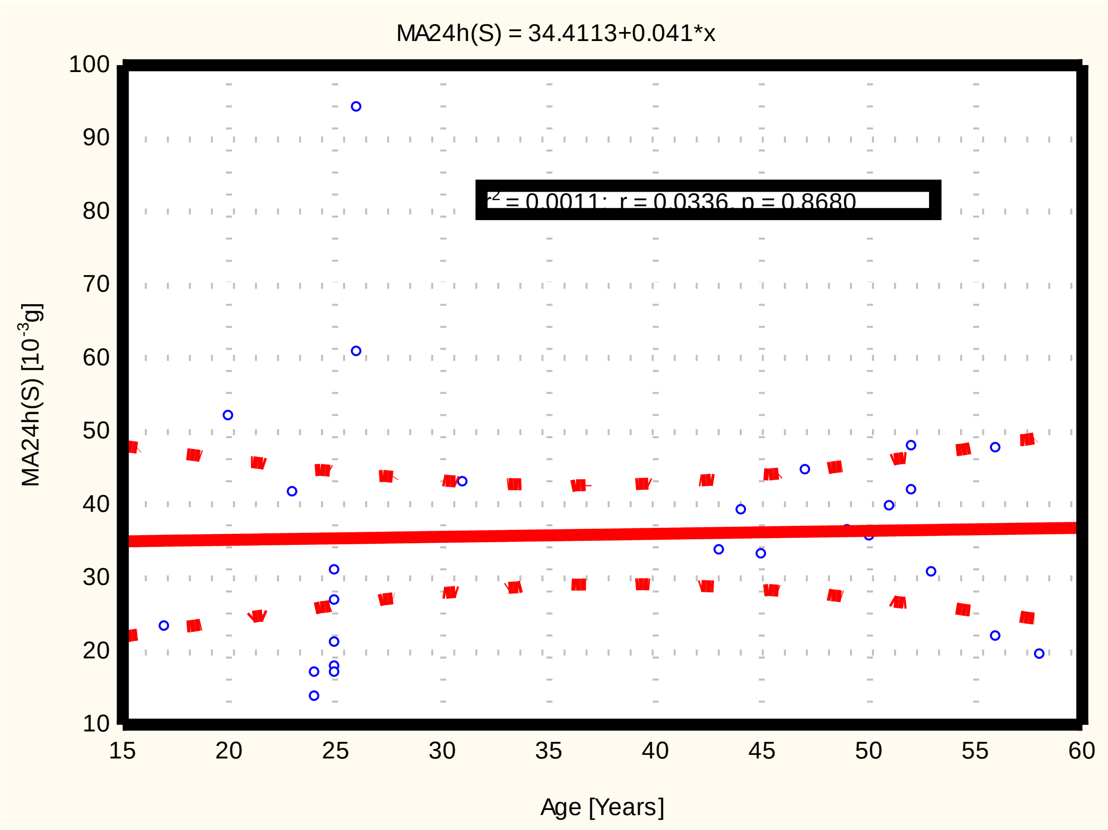

Fig. 4.8 - MA24h(S) against age.

The comparison between MA24h(S) and aPA is the only one that provides a significantly high Pearson's r ($r = 0.74$; $p < 0.001$); in the other cases no linear relationship is detectable between variables.

While scatterplots against BMI and aPA with a MA_{24h} index different from MA24h(S) make no sense, scatterplots against age can be done with the all of them, since we can expect a possible relationship between age and the motor behavior of each limb and not only waist: anyway, in none of the cases is detectable a significant linear relationship as it has been shown for MA24h(S) - Age.

It is possible to divide the 28 subjects original group into sets referred to the participants' occupations. The aim is to have sets filled with homogenous occupations and see if marked differences are detectable between them, the three subgroups extracted are:

- STUDENTS: this set is composed by the 10 students present in the original group of 28 subjects.
- OFFICE WORKES (white collars): this set is composed by the 9 office workers plus the 2 pharmacists present in the original group of 28 subjects.
- ACTIVE OCCUPATIONS (blue collars): this set is composed by the 4 warehousemen, the sale agent, the riding instructor and the cook present in the original group of 28 subjects.

The following **Table4.3**, **Table4.4** and **Table4.5** summarize the MA_{24h} descriptive statistics for the subgroups just described.

Tab. 4.3 - Descriptive statistics for the MA_{24h} indexes of the subgroup STUDENTS.

STUDENTS					
INDEX	**#N of subjects computed**	**MEAN [10^{-3}g]**	**St. Dev. [10^{-3}g]**	**MAX [10^{-3}g]**	**MIN [10^{-3}g]**
MA24h(UR)	10	58.1	20.5	97.1	39.0
MA24h(UL)	8	47.6	15.7	82.1	35.4
MA24h(S)	10	26.3	12.3	52.2	13.9
MA24h(LR)	10	59.1	30.2	111.0	29.3

Tab. 4.4 - Descriptive statistics for the MA_{24h} indexes of the subgroup OFFICE WORKERS.

OFFICE WORKERS					
INDEX	**#N of subjects computed**	**MEAN [10^{-3}g]**	**St. Dev. [10^{-3}g]**	**MAX [10^{-3}g]**	**MIN [10^{-3}g]**
MA24h(UR)	11	84.6	18.0	117.9	62.6
MA24h(UL)	11	73.8	15.8	102.3	54.0
MA24h(S)	10	33.4	7.5	43.2	19.6
MA24h(LR)	10	80.1	21.5	121.7	49.7

Tab. 4.5 - Descriptive statistics for the MA_{24h} indexes of the subgroup ACTIVE OCCUPATIONS.

ACTIVE OCCUPATIONS					
INDEX	**#N of subjects computed**	**MEAN [10^{-3}g]**	**St. Dev. [10^{-3}g]**	**MAX [10^{-3}g]**	**MIN [10^{-3}g]**
MA24h(UR)	7	107.2	23.2	149.3	79.2
MA24h(UL)	7	96.8	22.2	141.5	74.8
MA24h(S)	7	53.3	19.6	94.4	35.8
MA24h(LR)	7	127.5	31.6	174.4	76.0

Figure4.9, **Figure4.10**, **Figure4.11** and **Figure4.12** refer to boxplots linked to the previous group; in particular each boxplot compares an specific MA_{24h} index between the three groups.

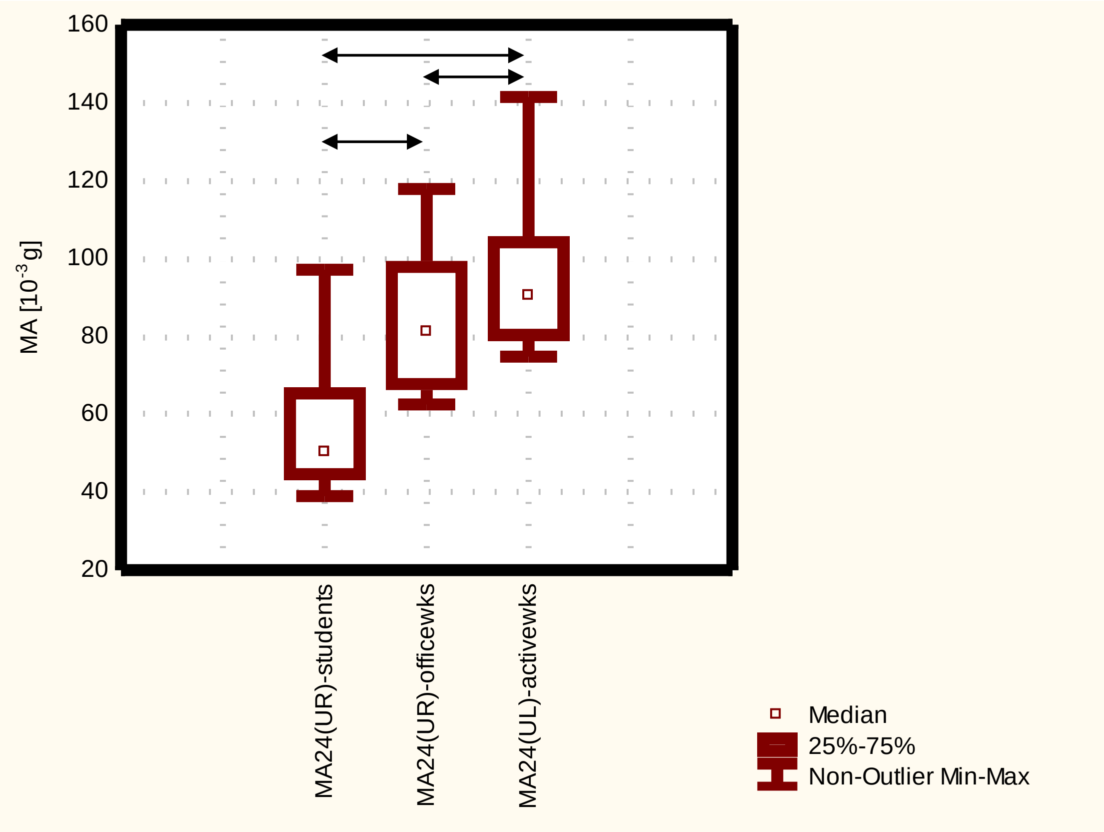

Fig. 4.9 - Comparative boxplot for the MA24h(UR) index between occupations groups.

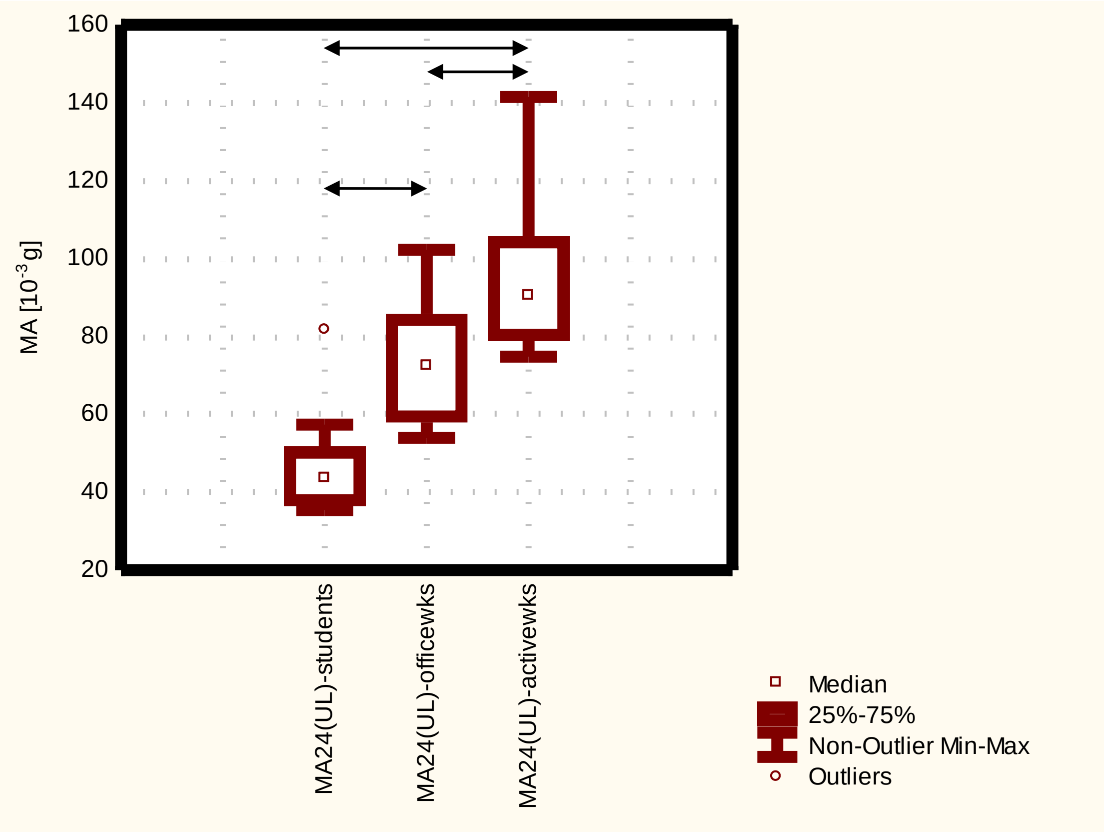

Fig. 4.10 - Comparative boxplot for the MA24h(UL) index between occupations groups.

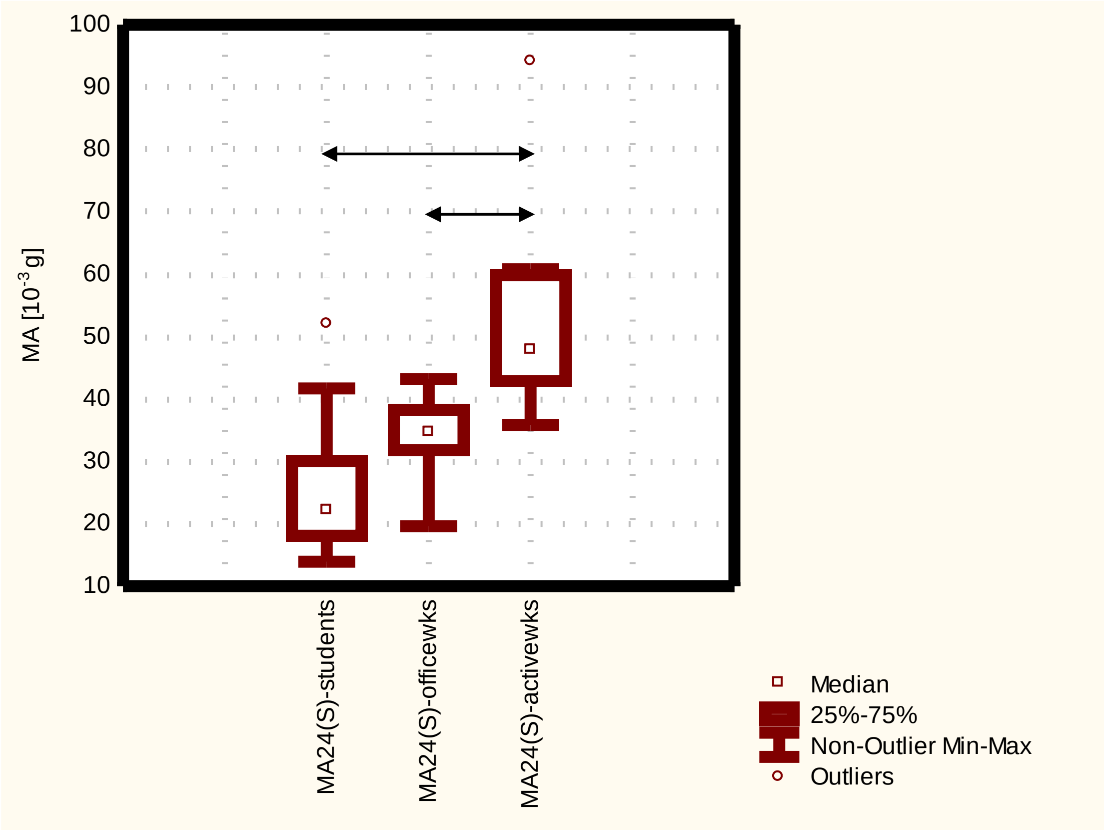

Fig. 4.11 - Comparative boxplot for the MA24h(S) index between occupations groups.

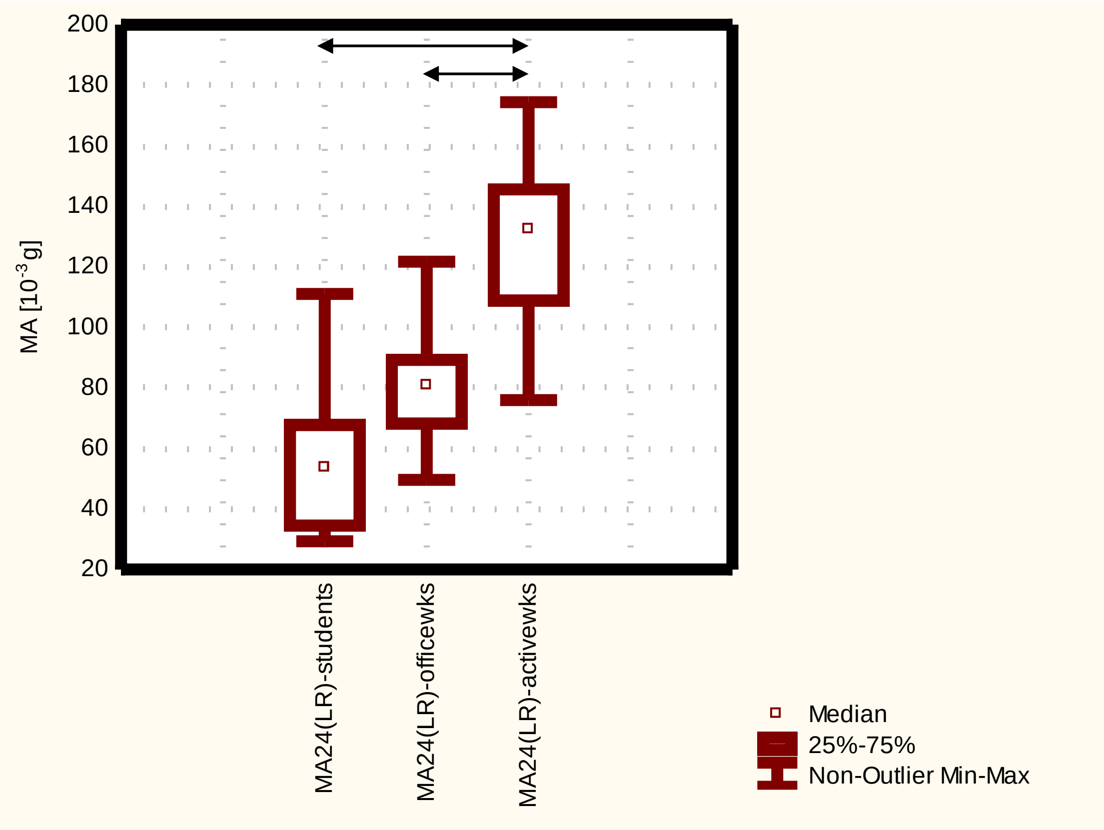

Fig. 4.12 - Comparative boxplot for the MA24h(UR) index between occupations groups.

The results of a t-test ($\alpha = 0.05$) on the means for the MA_{24h} indexes of each of the three groups, are substantially comparable to those showed in **Table4.2** when a t-test is computed for the same indexes on the whole group of 28 subjects: significant differences ($p < 0.001$) between indexes are detectable only in the cases in which is involved MA24h(S).

A comparative t-test is possible also between the same indexes but across the groups, **Table4.6** shows the outcomes of this statistic tests. Observing this table appears that just two comparisons (MA24h(S) -Students vs MA24h(S) - Office Workers and MA24h(LR) - Students vs MA24h(LR) - Office Workers) do not present a significant p-value ($p < 0.05$) for the means.

Tab. 4.6 - t-test results for MA_{24h} indexes when the same index is tested between subgroups.

INDEXES	Comparison	p-value
MA24(UR)	Stud vs O.workers	0.005
MA24(UR)	Stud vs A.occup	0.000
MA24(UR)	O.workers vs A.occup	0.033
MA24(UL)	Stud vs O.workers	0.002
MA24(UL)	Stud vs A.occup	0.000
MA24(UL)	O.workers vs A.occup	0.020
MA24(S)	Stud vs O.workers	0.135
MA24(S)	Stud vs A.occup	0.003
MA24(S)	O.workers vs A.occup	0.009
MA24(LR)	Stud vs O.workers	0.090
MA24(LR)	Stud vs A.occup	0.000
MA24(LR)	O.workers vs A.occup	0.002

4.2 AR_{24h} : Normative Values of Activity Ratio Indexes

Some question we wish to answer:

- ✓ *Do actually AR_{24h} indexes express a different information from MA_{24h} indexes?*
- ✓ *Is the preponderance level expressed by AR_{24h} indexes consistent with the results from MA_{24h} global motor activity ?*
- ✓ *Does the asymmetry between the upper limbs, in healthy people, determined by handedness?*
- ✓ *Have the AR_{24h} indexes relationships with sex or age?*

For each subject were computed also five **Activity Ratio** (AR) indexes for the 24h monitorings. The AR_{24h}, as described in Materials and Methods, are able to better quantify a state of asymmetry or preponderance among the two extremities involved in the case considered.

The five different AR_{24h} are listed below:

- **AR24h(UR,UL)**: index computed between Upper Right and Upper Left device.
- **AR24h(LR,UR)**: index computed between Lower Right and Upper Right device.
- **AR24h(UR,S)**: index computed between Upper Right and Sacrum device.
- **AR24h(UL,S)**: index computed between Upper Left and Sacrum device.
- **AR24h(LR,S)**: index computed between Lower Right and Sacrum device.

Table4.7 shows the descriptive statistics for the AR24h indexes, **Figure4.13** refers to a boxplot between them, **Figure4.14** is the boxplot when the variables are grouped by sex.

Fig. 4.7 - Descriptive statistics for the AR_{24h} indexes.

INDEX	#N of subjects computed	MEAN [%]	St. Dev.	MAX [%]	MIN [%]
AR24h(UR,UL)	26	7.5	6.3	22.4	-2.3
AR24h(LR,UR)	27	26.9	15.4	56.1	-7.0
AR24h(UR,S)	27	44.9	10.3	63.7	19.5
AR24h(UL,S)	25	38.5	10.7	59.0	17.9
AR24h(LR,S)	26	55.3	7.2	65.1	34.4

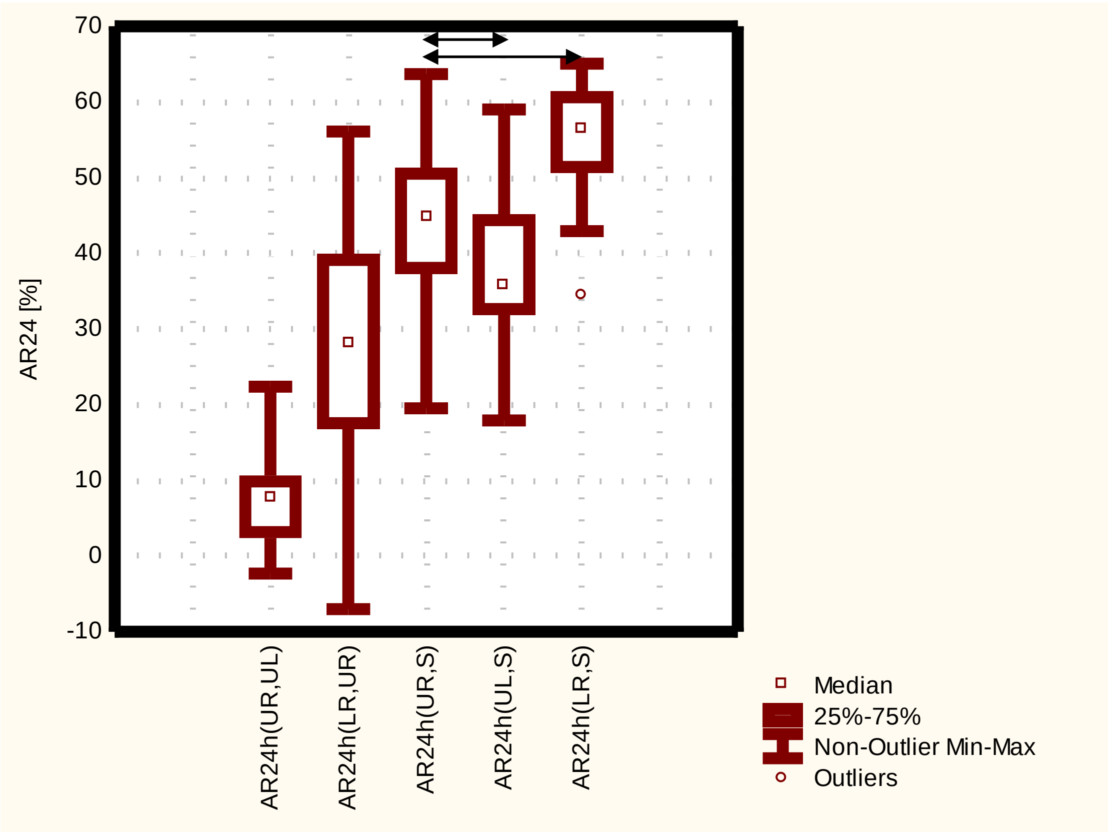

Fig. 4.13 - AR_{24h} indexes comparative boxplot.

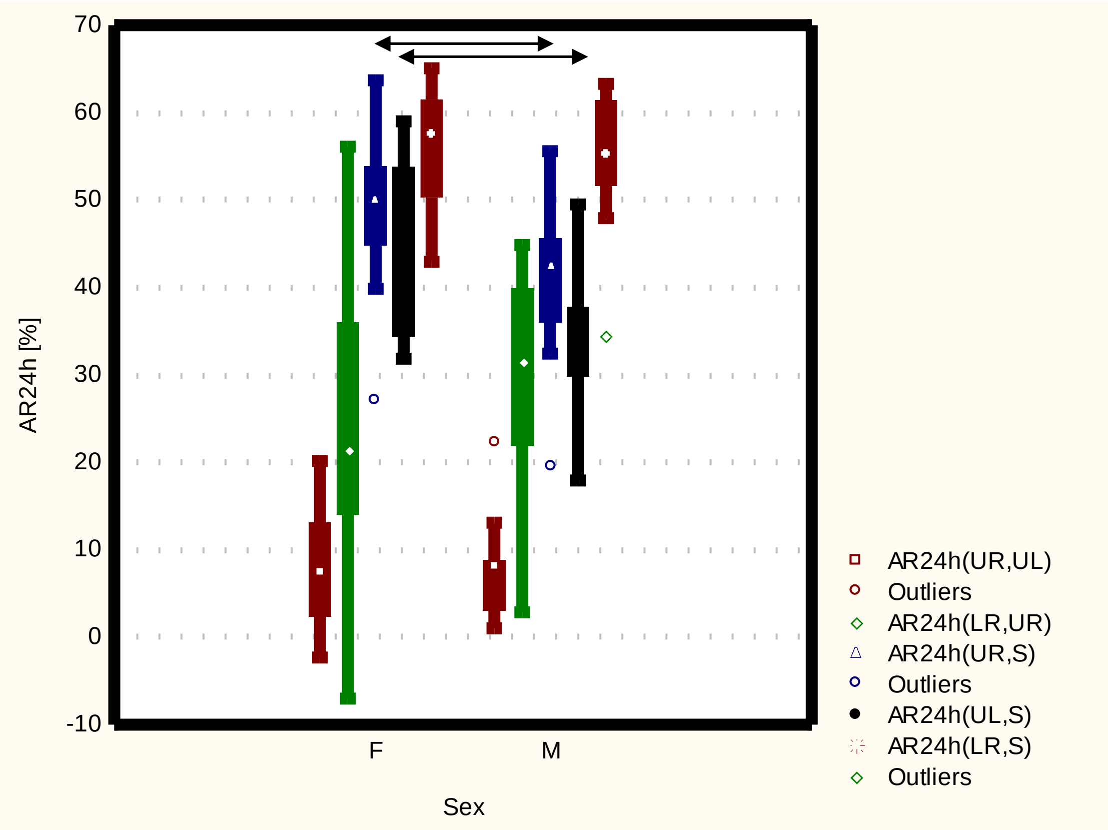

Fig. 4.14 - AR_{24h} indexes grouped by sex, comparative boxplot.

Table4.8 and **Table4.9** show the outcomes for t-tests ($\alpha = 0.05$) on AR24h indexes and the same indexes grouped by sex, respectively.

Tab. 4.8 - t-tests results for AR_{24h} indexes.

INDEXES	p-value
AR24h(UR,S)vAR24h(UL,S)	0.032
AR24h(UR,S)vAR24h(LR,S)	0.000

Tab. 4.9 - t-test results for AR_{24h} indexes grouped by sex.

INDEXES	p-value
AR24h(UR,UL)	0.943
AR24h(LR,UR)	0.428
AR24h(UR,S)	0.027
AR24h(UL,S)	0.007
AR24h(LR,S)	0.727

Figure4.15 is a scatterplot between the Edinburgh Handedness Inventory Test (Oldfield) and AR24h(UR,UL); the Pearson's r ($r = 0.28$) is not enough to represents a valid linear relationship.

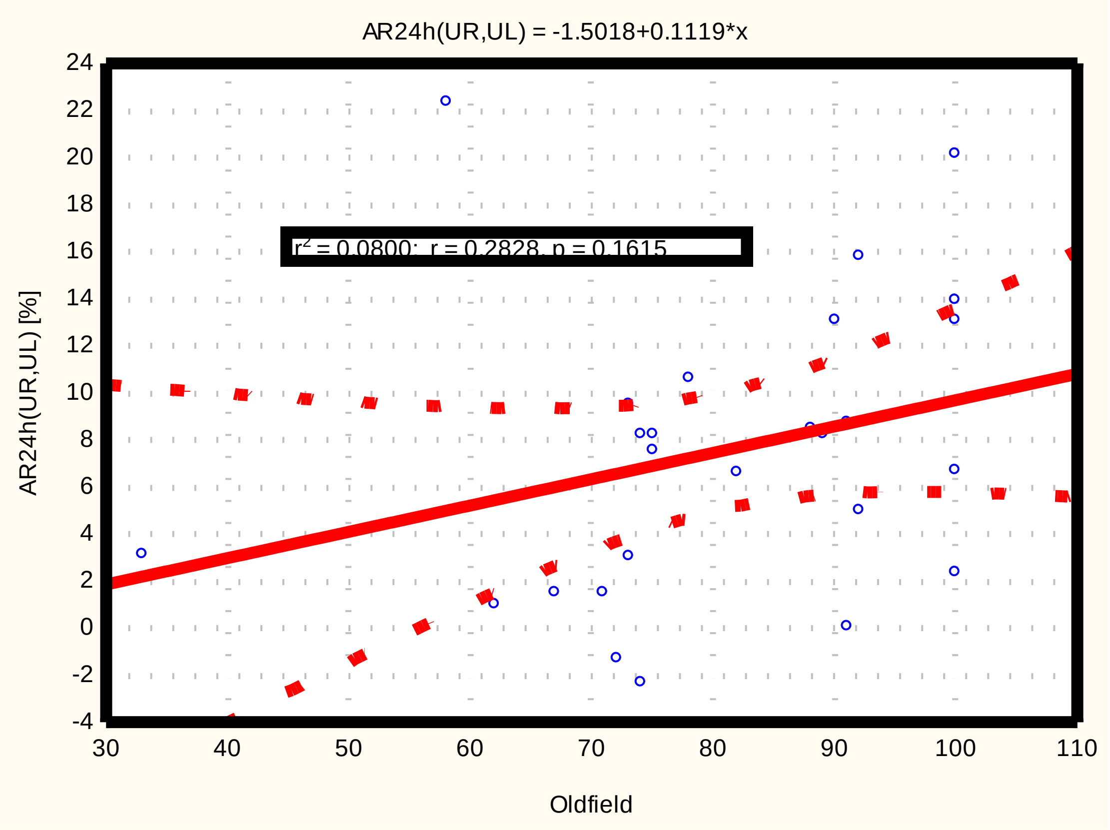

Fig. 4.15 - AR24h(UR,UL) against Oldfield.

If we classify the subjects for a clear lateral prevalence in relation to the Oldfield's test outcomes (right-handed for index above or equal to 70%; left-handed for index below or equal to -70%; ambidextrous for any other value) **Table4.10** summarizes the results.

Tab. 4.10 - Descriptive statistics for AR_{24h}.

Handedness	#N of subjects computed	AR24h(UR,UL) mean (across subjects)	AR24h(UR,UL) std (across subjects)
RIGHT (≥ 70)	22	7.6%	5.6%
Ambidextrous	4	7.0%	10.2%
LEFT(≤ -70)	0	/	/

Scatterplots among AR24h(UR,S) - AR24h(UL,S) and AR24h(UR,S) - AR24h(LR,S) show a marked linear relationship ($r = 0.83$, $p < 0.001$) just for the first couple, or alternatively for the indexes that compare contro-lateral upper limbs with sacrum, **Figure4.16**.

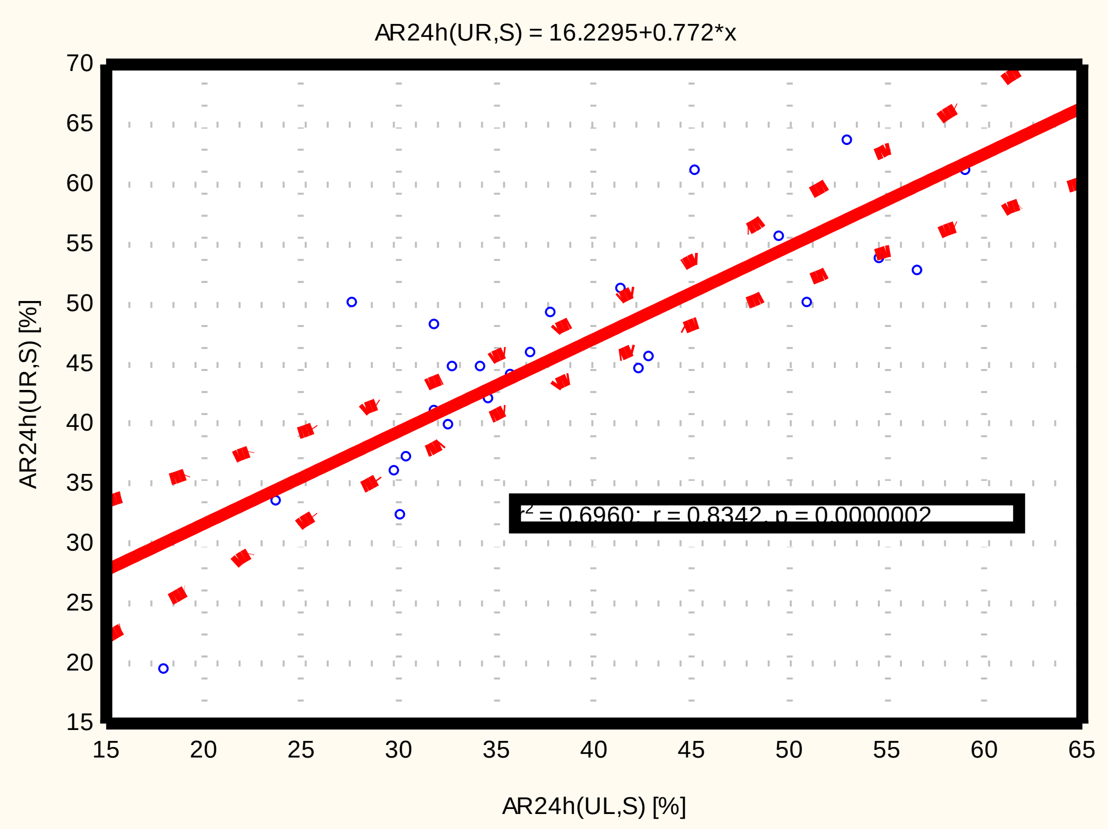

Fig. 4.16 - AR24h(UR,S) against AR24h(UL,S).

As for the MA24h indexes none linear relationship is detectable whether are scatterplotted the AR24h indexes against age.

As done for the MA_{24h} indexes, below are reported tables (**Table4.11**, **Table4.12** and **Table4.13**) and boxplots (following figures) when the AR_{24h} indexes are computed dividing the 28 subjects into the three groups homogeneous for occupations.

Tab. 4.11 - Descriptive statistics for the AR_{24h} indexes of the subgroup STUDENTS.

STUDENTS					
INDEX	#N of subjects computed	MEAN [%]	St. Dev.	MAX [%]	MIN [%]
AR24h(UR,UL)	8	7.7	3.9	13.1	1.6
AR24h(LR,UR)	10	28.8	15.6	42.8	2.9
AR24h(UR,S)	10	41.8	10.2	61.2	27.2
AR24h(UL,S)	8	36.1	10.6	59.0	23.7
AR24h(LR,S)	10	55.7	6.6	63.3	46.4

Tab. 4.12 - Descriptive statistics for the AR_{24h} indexes of the subgroup OFFICE WORKERS.

OFFICE WORKERS					
INDEX	#N of subjects computed	MEAN [%]	St. Dev.	MAX [%]	MIN [%]
AR24h(UR,UL)	11	8.6	8.2	22.4	-2.3
AR24h(LR,UR)	10	23.8	19.1	56.1	-7.0
AR24h(UR,S)	10	51.5	7.8	63.7	37.3
AR24h(UL,S)	10	43.9	10.7	56.6	27.7
AR24h(LR,S)	9	56.2	6.3	62.9	42.9

Tab. 4.13 - Descriptive statistics for the AR24h indexes of the subgroup ACTIVE OCCUPATIONS.

ACTIVE OCCUPATIONS					
INDEX	**#N of subjects computed**	**MEAN [%]**	**St. Dev.**	**MAX [%]**	**MIN [%]**
AR24h(UR,UL)	7	5.7	5.2	15.8	1.0
AR24h(LR,UR)	7	28.7	9.3	45.2	19.7
AR24h(UR,S)	7	40.0	9.8	48.3	19.5
AR24h(UL,S)	7	33.6	8.5	42.9	17.9
AR24h(LR,S)	7	53.6	9.7	65.1	34.4

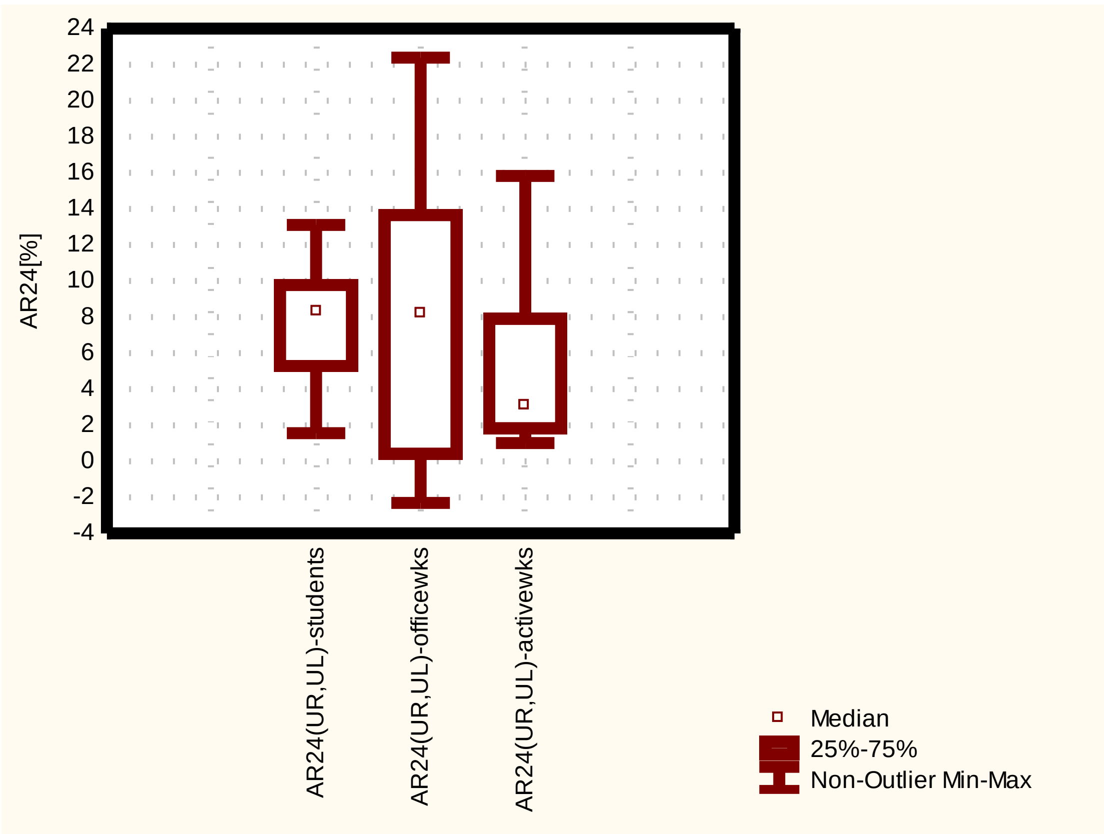

Fig. 4.17 Comparative boxplot for the AR24h(UR,UL) index between occupations groups.

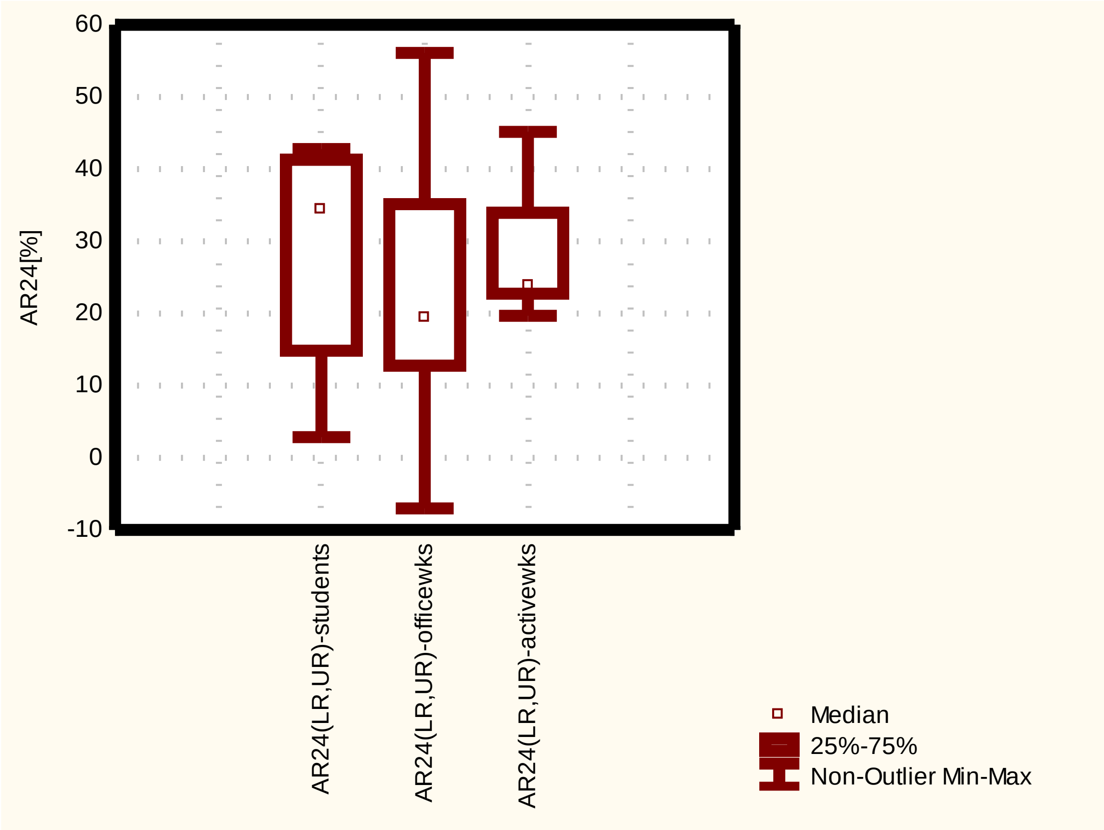

Fig. 4.18 Comparative boxplot for the AR24h(LR,UR) index between occupations groups.

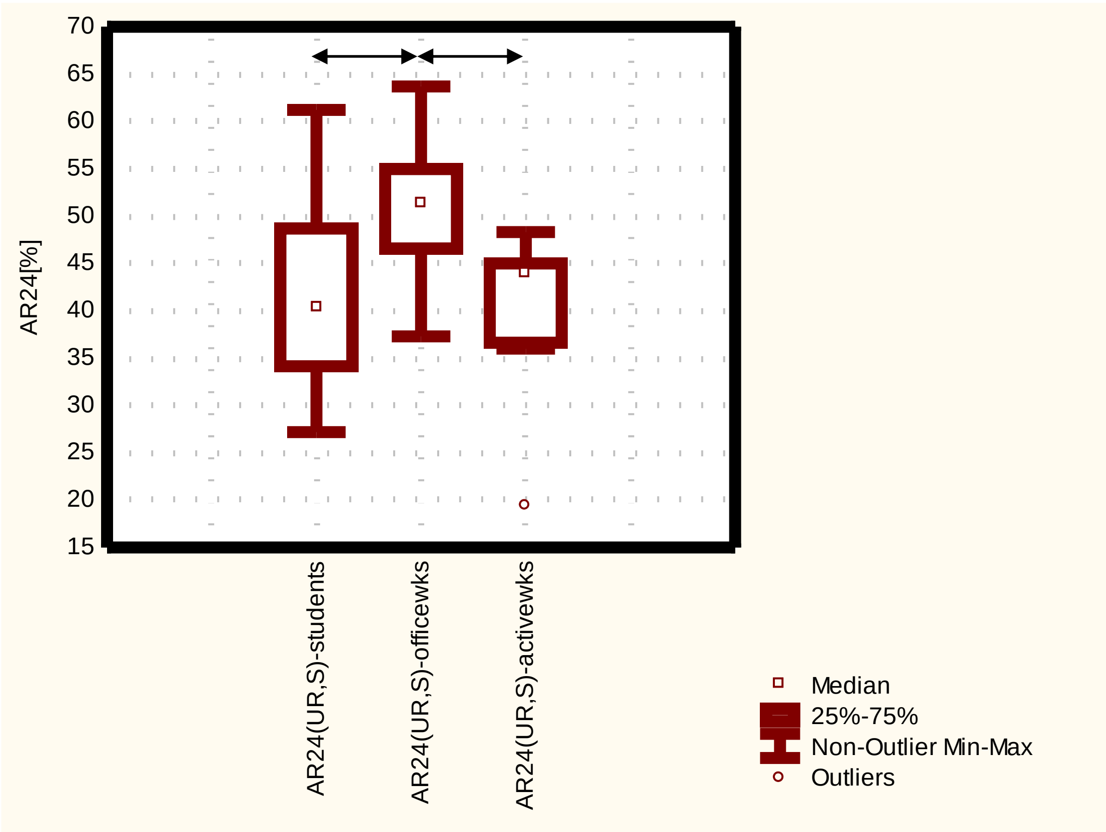

Fig. 4.19 Comparative boxplot for the AR24h(UR,S) index between occupations groups.

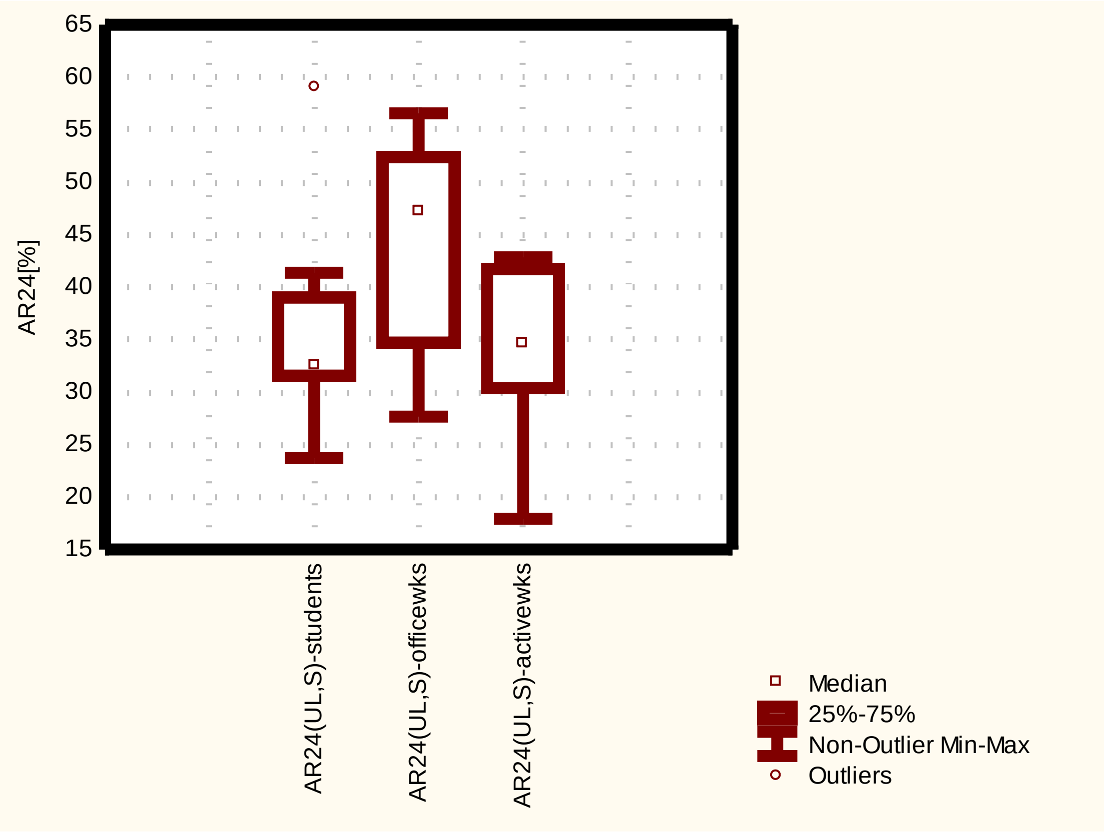

Fig. 4.20 Comparative boxplot for the AR24h(UL,S) index between occupations groups.

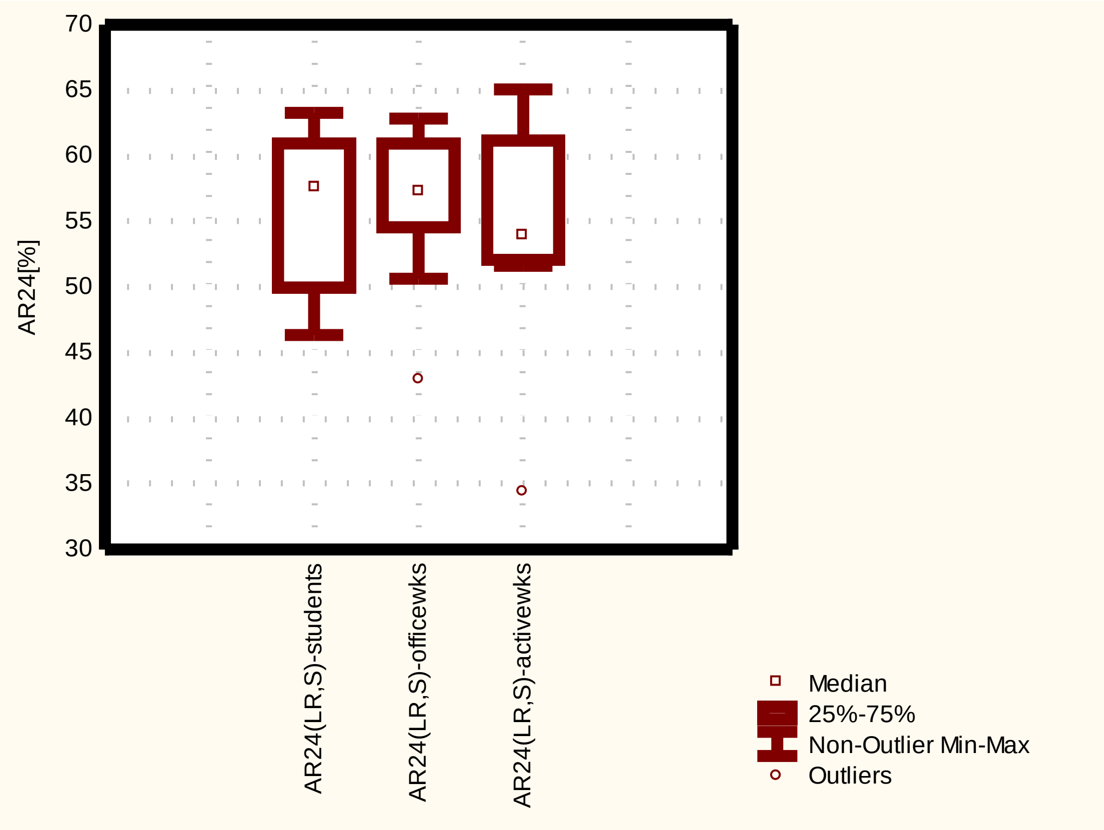

Fig. 4.21 Comparative boxplot for the AR24h(LR,S) index between occupations groups.

Table4.14 shows the results for t-tests ($\alpha = 0.05$) performed for the AR24h indexes across the groups.

Tab. 4.14 - t-test results for AR_{24h} indexes when the same index is tested between subgroups.

INDEXES	Comparison	p-value
AR24h(UR,UL)	Stud vs O.workers	0.770
AR24h(UR,UL)	Stud vs A.occup	0.404
AR24h(UR,UL)	O.workers vs A.occup	0.408
AR24h(LR,UR)	Stud vs O.workers	0.526
AR24h(LR,UR)	Stud vs A.occup	0.990
AR24h(LR,UR)	O.workers vs A.occup	0.537
AR24h(UR,S)	Stud vs O.workers	0.027
AR24h(UR,S)	Stud vs A.occup	0.725
AR24h(UR,S)	O.workers vs A.occup	0.0164
AR24h(UL,S)	Stud vs O.workers	0.145
AR24h(UL,S)	Stud vs A.occup	0.618
AR24h(UL,S)	O.workers vs A.occup	0.051
AR24h(LR,S)	Stud vs O.workers	0.864
AR24h(LR,S)	Stud vs A.occup	0.603
AR24h(LR,S)	O.workers vs A.occup	0.527

4.3 The 15h INDEXES

Some question we wish to answer:

- ✓ *What does it happen to both MA_{24h} and AR_{24h} indexes when we consider only daytime actigraphic recordings and discard the night/sleep period?*

All the indexes previously described were computed also on a restricted 15 hours sequence, extracted from the original one focusing the attention only on the daily hours of activity: in particular discarding the nocturnal hours from 21:00 pm to 06:00 am [23].

Table4.15 shows the descriptive statistics for both the MA and AR indexes when the acquisitions are reduced to 15 hours. The MA_{15h} values are in [10^{-3}g], the AR_{15h} in [%].

Tab. 4.15 - Descriptive statistics for the MA_{15h} and AR_{15h} indexes.

INDEX	#N of subjects computed	MEAN	St. Dev	MAX	MIN
MA15h(UR)	28	111.1	40.5	215.0	46.4
MA15h(UL)	26	98.8	38.1	204.1	42.5
MA15h(S)	27	49.2	25.1	136.0	15.3
MA15h(LR)	27	121.3	58.1	248.5	34.5
AR15h(UR,UL)	26	7.3	6.3	22.7	-3.2
AR15h(LR,UR)	27	28.0	15.8	56.9	-6.5
AR15h(UR,S)	27	44.0	11.1	63.9	19.3
AR15h(UL,S)	25	37.7	11.5	58.5	18.0
AR15h(LR,S)	26	55.5	7.3	65.2	33.3

In terms of graphic relationships nothing varies from what is showed for the 24h indexes, both MA_{15h} and AR_{15h}. When the t-tests are performed the significant differences present for the 15h indexes are the same seen for the 24h-indexes, the only diversities are:

- For the male-MA15h(UR) and female-MA15h(UR) H_0 is no more rejected, a $p = 0.317$ against the previous $p = 0.026$; so there is no difference between each of the MA_{15h} when grouped by sex.
- AR15(UR,S) vs AR15(UL,S) still present a significant difference, but the p-values increases till the on the edge value $p = 0.049$.

Table4.16 and **Table4.17** presents the t-test ($\alpha = 0.05$) outcomes when the indexes MA24h - MA15h and AR24h - AR15h are respectively compared. The two tables show that there is a significant difference in the normative values between the cases in which the sleep hours are considered or not just for the MA indexes, while no difference is shown by the AR indexes.

Tab.4.16 - t-test results for MA24h indexes against MA15h indexes.

INDEXES	p-value
MA24h(UR)vMA15h(UR)	0.002
MA24h(UL)vMA15h(UL)	0.004
MA24h(S)vMA15h(S)	0.026
MA24h(LR)vMA15h(LR)	0.008

Tab.4.17 - t-test results for AR24h indexes against AR15h indexes.

INDEXES	p-value
AR24h(UR,UL)vAR15h(UR,UL)	0.883
AR24h(LR,UR)vAR15h(LR,UR)	0.797
AR24h(UR,S)vAR15h(UR,S)	0.744
AR24h(UL,S)vAR15h(UL,S)	0.795
AR24h(LR,S)vAR15h(LR,S)	0.917

4.4 TEST-RETEST RELIABILITY

Some question we wish to answer:

- ✓ *After a retest session, how the indexes values appear compared to those of the first acquisition in healthy subject with a week routine?*
- ✓ *Is it observable a test-retest reliability? (even if with a small set of subject tested)*

Five subjects (2 men and 3 women with age ranged from 23 to 58 years, mean 43) repeated the monitoring after the first assessment in order to assess test-retest reliability of the indexes. When possible, in relation to the availability of the participants, the retest session took place in the same day of the week of the first acquisition in order to minimize any confounding factor.

Table4.18, shows the Δ (test values - retest values) for the descriptive statistics of the subgroup undergone to the retest session.

Tab. 4.18 - Descriptive statistics for 5 subjects test retest comparison: table shows Δ values (test-retest) for the 24h indexes.

TEST - RETEST 24h					
INDEX	**#N**	**ΔMEAN**	**ΔSt. Dev**	**ΔMAX**	**ΔMIN**
MA24h(UR)	5	-1.8	-1.0	-2.9	2.3
MA24h(UL)	5	-1.0	1.5	-0.4	2.6
MA24h(S)	5	1.4	5.8	12.8	-1.6
MA24h(LR)	5	6.2	14.6	38.1	0.8
AR24h(UR,UL)	5	-0.1	1.8	0.7	-3.2
AR24h(LR,UR)	5	6.6	0.2	8.8	8.1
AR24h(UR,S)	5	-3.2	-2.5	-4.5	-3.7
AR24h(UL,S)	5	-2.7	-0.3	-5.1	-1.6
AR24h(LR,S)	5	1.7	0.9	4.8	0.6

It is possible to compute the Pearson's r for the two session of each subject considering each single index, **Table4.19** refers to these r coefficients..

Tab. 4.19 - Pearson's r between test and retest session for all MA24h, AR24h, MA15h and AR15h indexes.

	MA (UR)	MA (UL)	MA (S)	MA (LR)	AR (UR,UL)	AR (LR,UR)	AR (UR,S)	AR (UL,S)	AR (LR,S)
r	0.75	0.69	0.54	0.24	0.55	0.29	0.74	0.81	0.20

4.5 Acceptability and feasibility of monitoring with GENEActiv

Some question we wish to answer:

- ✓ *How participants have perceived an experience with a multiple wearable sensors setup?*
- ✓ *Is it GENEActiv a comfortable wearable actigraph ?*

One of the questionnaire delivered to the participant was related to the acceptability of the GENEActiv devices during the 24h monitoring. Below are reported the five questions to which the subject was asked to answer, for each question he/her could choose a value of intensity from zero to five (0-No, 1-Slightly, 2-Mildly, 4-Quite enough, 5-Much) and possibly fill with personal notes.

Questions:

1. Did the actigraphs interfere in the progress of your normal daily activities? If YES, how?
2. Did the actigraphs interfere with the quality of sleep? If YES, how?
3. During the 24h of acquisition were you conscious of wearing the devices?
4. Did the actigraphs cause discomfort, itching or skin irritation? + personal notes
5. Did wear the actigraphs cause embarrassment? + personal notes

Table4.20 summarizes the answers of the 28 subject, is it worth noting that those who repeated the measure for the test-retest reliability were also asked to refill a new acceptability questionnaire, so the following table is based on 33 questionnaires (28 test + 5 retest). The number presented in each cell of Table4.20 stands for the number of answer at the question in the column with an answer of intensity a showed in row.

Tab. 4.20 - Summary of the acceptability questionnaire answers.

Answer	1. Did actigraphs interfere in daily activities?	2.Did actigraps with sleep?	3. Were you aware of wearing the actigraphs?	4. Did actigraphs cause discomfort, itching or skin irritation?	5. Did actigraphs cause embarrassment?
0-No	29	29	0	22	33
1-Slightly	3	2	17	8	0
2-Mildly	1	2	9	0	0
4-Quite enough	0	0	5	2	0
5-Much	0	0	2	1	0
Mean answer	0.15	0.18	1.76	0.55	0
Approximation	0	0	2	1	0

Taking into account the observed sample the acceptability results are totally satisfying, as the summary table show:

- the actigraphs seem not to disturb the common daily activities: the mean answer to the first question is substantially approximated to zero (0-No).
- the actigraphs seem not to disturb sleep: the mean answer to the second question is substantially approximated to zero (0-No).
- the complete actigrahs set is just mildly perceived: the mean answer to the third question is substantially approximated to two (2-Mildly).

- the actigraphs seem not to cause discomfort or irritation except isolated cases: the mean answer to the fourth question is substantially approximated to one (1-Slightly).
- the actigraphs seem not to cause embarrassment: the mean answer to the fifth question is substantially approximated to zero (0-No).

As previously reported, the participants had the opportunity to fill the questionnaire with personal notes related to the experience of wearing the GENEActiv devices, for the sake of completeness are reported some observation:

- six people reported a discomfort caused by the device positioned on the ankle, that, for this reason, becomes the less appreciated of the four actigraphs; the discomfort is likely due to the Velcro® strips that can become uncomfortable approaching the 24h.
- three people reported a discomfort caused by the device positioned on the sacrum; this device seem to cause bother when interfere with the trousers' belt or when it is wear by people who spent a lot of time sitting in the car.
- two people reported a slightly discomfort during sleep because of the device on the ankle and on sacrum respectively.
- two people reported a slightly discomfort in wearing clothes.

5. Discussion and Conclusions

The proposed study is a preliminary investigation on the long-lasting monitoring of motor activity using a setup of multiple wearable devices; in particular the experiment was carried on with the use of four actigraphs *GENEActiv Original* and with the use of specifically designed motor indexes.

Here are the primary guidelines adopted in the design of the experiment:

- The monitoring must last 24h in order to include the total motor activity of the subject acquired, also the night sleep period. The will is to monitor a person in his/her daily living environment and do not force him/her in a laboratory setting: emphasizing what is called *motor performance* against the *motor capacity* commonly analyzed in motor analysis laboratories (**Chapter1**).
- Use of a non-invasive and comfortable device (actigraph) suitable to be worn without nuisances during the whole monitoring.
- Positioning of sensors in order to assess either a COM-related global aspects and limbs-specific motor functions.
- Choice of a device having as outcomes raw measurements and not ready-made/post-processed proprietary "count units" or other predefined indexes.
- Definition and use of indexes of movement and activity ratio (limbs prevalence) completely invariant respect to the sensors orientations, but only determined by the sensors locations.

Important to dwell on the last point: the definition of indexes only determined by the sensors locations primarily derives from criticalities linked to the monitoring of upper limbs movements. The upper limbs are characterized by movements that may occur in any spatial direction and such occurrences may cause issues in the acquisition: an example are some commonly used indexes based on *"counts"* ; these indexes count the number of time an acceleration threshold is exceeded and on this amount base the overall quantification of movement.

This approach is valid and widespread but in this case a controlled orientation of the sensors is mandatory and not easy to achieve because of the complexity of upper limbs movements (in particular whether an uniaxial device is used). On the contrary, indexes independent from sensor's orientation fit better to track upper limbs movements without this kind of issues.

Once described the choices that led to the definition of the motor indexes used, it is important to dwell on the epoch duration. In Material and Methods (**Chapter3.4**) it was highlighted that a 1-minute epoch was chosen as basic brick of the around-the-clock registration, so that each monitoring can be divided into 1440 epochs. In this choice there are not particular rules to deal with: the real important thing is that the epoch duration should identify a time span which is not to small, neither too large at the same time; in this way the 60s epoch is as much arbitrary as reasonable as minimum unit and it was chosen because already adopted in previous studies retrieved in literature.

5.1 Discussion of the experimental results - MA_{24h}

Observing the descriptive statistics and relative boxplot (**Tab.4.1**, **Fig.4.1**) for the MA_{24h} indexes, the lower limb is the one with the larger mean value between the four points of measure, followed by both upper limbs and, finally, by the sacrum; in particular, the sequence LR-UR-UL-S (for the point with the higher mean value to the lower) is respected by the 61% of the participants (17 out of 28), when it is not, in the 73% (8 of 11) of the remaining cases the sequence is UR-UL-LR-S with the prevalence of the upper limbs. These results reflect some expectations, highlighting the validity of the MA indexes:

- The sacrum is the body point with the lower mean value, being an approximation of the body center of mass it is substantially involved only in the activities that assume the whole body movement (e.g., walk), while its movement is limited or absent in sedentary activities. In fact, it is possible to correlate the highest values in the group ($> 40\ mg$) with the subjects that have an active occupation (i.e., the warehousemen, the riding instructor) or reported a sport activity in the diary relative to the day of the acquisition. Its more limited movement, makes the sacrum the only body point with a behavior (in terms of amplitude and variability of the related MA index) significantly different ($p < 0.001$) from the other segments measured; this is showed in the comparative t-tests between MA_{24h} (**Tab.4.2**).

- The ankle device is the one that experiences the major accelerations, this is due to the relation between the lower limbs movement and the locomotor activity. The four lowest and four highest MA values are a significant example: the lowest ones belong to four students who, according to the diary, experienced brief displacements or house activities, the highest ones belong to people (e.g., the warehouseman, the riding instructor) who filled the diary with non-sedentary activities. The high linear relationship ($r = 0.92, p < 0.001$) between MA24h(LR) and MA24h(S) confirm what is said in the previous point: higher values of both these two body points MA indexes are linkable to non-sedentary activities.
- Speaking about healthy subjects the upper limbs have, as expected, a similar behavior (mean difference for the 24h is just 9.14 mg with a standard deviation of 7.78, while the correlation coefficient between the two is $r = 0.96$, $p > 0.001$, **Fig.4.4**). The slightly higher values of UR (in only one case UL > UR) are imputable to the right-handedness of all the participant. The subject who presented the UL > UR value was reacquired (just on wrists), in this second registration the value turned into UR > UL, so that the previous result is probably due to chance: some specific activity the subject did in the day of the first acquisition made an accidental higher use of the left arm against the right, although the subject is right-handed.

  Also the upper limbs are highly correlated with MA(S) (**Fig.4.3**), this relationship is probably always due to the sacrum activity: an activity that imply the movement of the pelvis imply also the movement of upper limbs (e.g., walk is a typical example), so that who present high MA24h(S) values, likely will show high value also for MA24h(UR) and MA24h(UL); the opposite it may not be true, you can imagine high MA24h(UR) or MA24h(UL) values associated to a low MA24h(S) because of sedentary activities involving a large use of upper limbs. Anyhow this is not frequent: manual activities need to be intense and/or frequent not to be hidden from upper limbs movement of other origin. The high correlation ($r = 0.91$, **Fig.4.5**) among the indexes of ipsilateral limbs MA24h(UR) and MA24h(LR), likely derive just from the locomotion activities of the subjects during the acquisition.

When these indexes are grouped by sex (**Fig.4.2**) just *male-MA24h(UR)* vs *female-MA24h(UR)* shows a significant difference for a t-test $\alpha = 0.05$ ($p = 0.026$). The result is likely due to chance: in general is observed an higher average value of the females' indexes against the males' ones, this may be related to the fact that 50% of women reported a non sedentary work activity or a sport activity in the diary, while this is true just for the 28% of men. The sport activities reported are also consistent with what was reported on questionnaires: as highlights **Table3.3**, the women of the group are used to practice sport more often than man, although more men than women practice sport in general. At the same time, if the sport activity is the actual answer to this difference, you should expect differences also for MA24h(S) and MA24h(LR) between sex, but this is not the case. Thus, even if between the male and female indexes a statistically relevant difference is not observable except for the UR index, it is worth noting that the female mean values tends to be higher than the corresponding male's, while the male maximums are greater than the corresponding female's. A possible justification to the MA24h(UR) male and female index significant difference, could be found in some female-typical daily activities (e.g., household activities as reported in questionnaire): this could explain mean values slightly higher than men, at the same time the males maximums are imputable to the general greater male athleticism, that allows to express higher extreme values than females when compared in similar circumstances; actually, by chance, this may be the answer on what led to the significant MA24h(UR) unbalancement in the two groups

Being a sign of global motor activity, with the due approximations, MA24h(S) has been compared to variables as the BMI (Body Mass Index)(**Fig.4.6**) and aPA (approximate Physical Activity hours per week)(**Fig.4.7**). This latter aPA is a value independently provided by the participant through the questionnaires on the basis of his/her personal perception, the document referred to aPA as

"the physical activity approximately experienced during the week (in hours): this voice must be considered broadly, in addition to actual physical activity (i.e., sport) is possible to consider in the total count also activities as reach the workplace by bike etc.".

While BMI can't be defined linearly related to MA24h(S), this can be done with aPA confirming one more time the assumptions described before. The correlation is good ($r = 0.74$, $p < 0.001$), but not perfect, and this is likely due both to the rough answers of the subjects and circumstances (exogenous factors): a subject may not have practiced sport in the day of the registration even if he/she is used to during the week, but he/she may have anyway an high/low MA24h(S) value for some reasons (from this the importance of a diary). In any way, from the two graphs is possible to say that not necessarily who has an higher BMI does more physical activity (it is also true that among the subjects nobody shows weight-related diseases and so nobody needs to put particular attention on physical exercise), but surely who reported high aPA values shows high MA24h(S): looking at the graph this is particularly true for the higher values from which the final correlation result is more dependent; so if someone reports an high aPA value (because of a particular occupation, or a particular intense sport activity) is likely to find an high MA24h(S); while who does a mild sport activity or is not especially active in his/her occupation will show interchangeable MA24h(S) values depending on the actually daily activity.

None of the MA_{24h} indexes showed a correlation with the age of the subjects (e.g., MA24h(S) - Age, **Fig.4.8**). This outcome is to be interpreted with the age variability of the group: all the subjects has an age ranging from 18 years to 58 (**Tab.3.2**), being all healthy from a motor point of view, besides the eventual sport activity, we do not expect differences between the motor behavior of a young boy/girl (e.g., 24 years) and a mature adult (e.g., 50 years): in fact the age-related motor reduction must be intended in terms of a capacity limit, but normal life activities do not imply reaching these limits every day. In this way should be interesting acquire elderly people, not physically impaired as well, and evaluate the presence of a significant decrease in mobility and related indexes for daily activities comparable to those of the group here discussed.

The 28 subjects group was also splitted into three subgroups homogeneous in the participants occupations (**Chapter4.1**): STUDENTS, OFFICE WORKERS, ACTIVE OCCUPATIONS. There are expectations for which STUDENTS and O.WORKERS should show similar motor behaviors, while different should be the one presented by the group of A.OCCUPATIONS.

Table4.3, **Table4.4** and **Table4.5** report the descriptive statistics for the three subgroups, **Figure4.9**, **Figure4.10**, **Figure4.11** and **Figure4.12** are boxplot comparing the same MA_{24h} of each group, **Table4.6** reports the outcomes for the cross-groups t-tests for the same MA_{24h} index.

The expectations for the subgroups motor behaviors are well respected:

- The three subgroups respect the global characteristics showed by the MA_{24h} indexes. In two groups (STUDENTS and ACTIVE OCCUPATIONS) the sequence for the MA_{24h} means from the higher to the lower is the one showed for the whole 28 subjects group (LR-UR-UL-S); the remaining group shows a UR-LR-UL-S sequence. The ratio between the MA24h means against MA24h(S) are maintained substantially unchanged. MA24h(UR) and MA24h(UL) have very similar behaviors with a slightly prevalence of UR in accordance with the right-handedness of all subjects. At last, once a t-test is done between the indexes of each group, MA24h(S) is the only index significantly different from those related to the other limbs.
- The three subgroups show significant differences for the upper limbs; each group is significantly different from the others, both considering the right arm and the left arm. An expectation could have been the one for which students and office workers would have shown similar upper limbs behaviors: the negative answer is likely due to the high upper limbs variability linked to the daily activities. LR variability is even higher, but also more easily to correlate to specific sources (locomotor activities), while the upper limbs outcomes highly depend on manual habits of the subjects: for this reason it is plausible think that you can find a difference also comparing groups thought similar; in this case the O.WORKERS showed an higher upper limbs activity than STUDENTS even if, intuitively, you may think a difference is not present due to the similar sedentary daily activities.
- STUDENTS and O.WORKERS have a not significantly different MA24h(S) behavior ($p = 0.135$), but both their MA24h(S) are significantly different from the one by A.OCCCUPATIONS ($p = 0.003$ and $p = 0.009$, respectively for STUDENTS and O.WORKERS).

- STUDENTS and O.WORKERS have a not different MA24h(LR) behavior ($p = 0.090$), but both their MA24h(LR) are significantly different from the one by A.OCCCUPATIONS ($p = 0.000$ and $p = 0.002$, respectively for STUDENTS and O.WORKERS).

The analysis on the MA_{24h} indexes when the subgroups are observed is consistent with the previous considerations: first of all the subgroups respect the global MA_{24h} characteristics proposed by the original group, then these findings confirm the previous assumptions for which high level of MA24h(S) and MA24h(LR) can be considered "*clear symptoms of non-sedentary activity*": in the case considered, is exactly the A.OCCUPATIONS group that presents the highest MA_{24h} values and, furthermore, shows value significantly different from what is shown by the other two subgroup (characterized by sedentary activities and so rightly not so different between them).

5.2 Discussion of the experimental results - AR_{24h}

The Activity Ratio AR_{24h} indexes, as said in Material & Methods (**Chapter 3.4**), have been designed to compare synchronously the activity recorded from each epoch of two different body points; they are not quantifying a simple difference between the mean activities, a value that can be extracted from the MA_{24h} values. In this terms, the described AR_{24h} differs from other proposed asymmetry or preponderance indexes which are based on an average activity. It is worth noting that AR_{24h} are independent from the time span considered, this because of the synchronicity assumption: in the computation of an AR_{24h}, the epochs with larger MA_e indexes are the most relevant for preponderance quantification, while the epochs with small MA values (e.g., sleep or resting related epochs) are expected to contribute less since the best-fitting line, used to define the index, is an eigen-vector which passes by the origin of the axes. This is the reason why the t-tests (**Tab4.16** and **Tab4.17**) show a significant difference between indexes computed for 24h and 15h just in the case of MA_{24h} and not for AR_{24h}: consider or not the night makes a big difference for MA indexes which strongly rely on the considered time span.

AR_{24h} normative values are reported in **Table.4.7**, **Figure4.13** is a comparative boxplot. The indexes computed can be divided into two groups: the first is composed by the AR_{24h} computed between limbs (controlateral as for AR24h(UR,UL) or ipsilateral as for AR24h(LR,UR)), the second by those AR_{24h} which compare the preponderance of a limb activity against the sacrum.

AR24h(UR,UL) is the index able to synthesize the behavior of the two upper limbs, quantitatively highlighting, whether present, an asymmetry. The outcome value is consistent with the findings of MA_{24h} indexes for upper limbs: in healthy subjects right and left arm have a comparable motor activity, this leads to an AR24h(UR,UL) significantly reduced in amplitude and variability (mean value of 7.5%, standard deviation of 6.3 translatable into a range of less than 25 percentage points); in accordance with the right-handedness of the group, all subjects except two showed a positive value for AR24h(UR,UL), the two only negative values are very low (-1.32% and -2.31%). The higher values for this asymmetry index (> 10%) are reported by students as well as active workers, but none of them reports in the diary some activities that should suggests an higher asymmetry of the upper limbs respect what is showed by the others participants: AR24h(UR,UL) is not dependant from macro-causes as the occupation, but more likely from personal manual habits; furthermore, the small range assumed by this variable in healthy people would suggest a good sensitivity when it will be used with impaired people (e.g., post stroke patients), who are likely to go out of this normality range. Further investigations are needed.

Rabuffetti et al. [23] showed a good correlation coefficient ($r = 0.66$, $p < 0.001$) for AR24h(UR,UL) and the outcomes of Oldfield's test which is also close to the results by Nagels [8]. In this study, **Figure.4.15**, seems that a linear relationship is absent ($r = 0.28$) between AR24h(UR,UL) and Oldfield; in any case the result do not suggest errors in the procedures. An explanation is that our group suffers the absence of left-handed people (on the contrary, present in the Rabuffetti's work), just with their presence is possible to imagine a robust assessment of any correlation: AR24h(UR,UL) is an asymmetry index, but Oldfield's value has not an extremely high resolution, so that, actually, there is not a relevant difference between subjects showing 100% or 70% as Oldfield's outcome. This experiment proposes just six ambidextrous (Oldfield between -70% and 70%), two of them do not have associated any AR24h(UR,UL) because of measurements issues, the other 4 present values are just a little bit lower than 70% and without left-handed participants values less than -70% are completely absent: it is impossible to expect a robust assessment of a possible correlation.

The two subjects mentioned before with a negative AR24h(UR,UL) have respectively a 72% and 74% Oldfield's score and are both office workers: the light preponderance of the left limb must be probably associated with chance, the activities done during the day of acquisition have pushed towards a little higher left hand usage although the right-handedness.

The other between-limbs AR_{24h} is AR24h(LR,UR): taking into account two ipsilateral extremities, this can not be considered as an index of asymmetry, but just as an *index of prevalence*. All subjects except one show positive values with a mean of 26.9%. The LR prevalence on UR in this large amount of subjects, is simply imputable to the locomotion activities and to the higher mean values the lower limbs experience globally during the day for this reason. It is worth noting that while MA_{24h} show higher LR mean values than UR in 61% of subjects, AR24h(LR,UR) presents a LR prevalence on UR in 96% of cases (27 out of 28), so that you can detect a positive AR24h(LR,UR) also in those cases which show a MA24h(UR) > MA24(LR): this is a clear example of how MA_{24h} and AR_{24h} actually express two different kind of information due to their nature. The subject with the negative AR24h(LR,UR) is an office worker and on the 24h acquisition diary reported more than three hours on car: these two elements could be an answer to his UR prevalence than what it is showed by the other participants.

The second group of AR_{24h} indexes is composed by AR24h(UR,S), AR24h(UL,S) and AR24h(LR,S): they express a prevalence of a limb against the movement of sacrum, comparing for definition the synchronous MA_e. All these three indexes have a similar variability (the standard deviations are 10.3, 10.7, 7.2 respectively) and their mean values reflect what was observed with the MA_{24h} indexes: LR is the limb that prevails more on sacrum, it is followed by the upper limbs with values slightly favorable to UR in accordance with the right handedness of subjects. Nobody presents a AR24h(UL,S) higher than AR24h(UR,S), even the two participants with the negative AR24h(UR,UL).

The p-values of the t-test (**Tab.4.8**) shows a significant difference among these three indexes: the p-value between limbs is less significant ($p = 0.032$) compared to the one referred to two ipsi-later limbs ($p = 0.000$), this remarks again the shlightly similar behaviours of left and right arm in healthy people, with values corresponding to a right handedness of the group.

The results complete with new information what presented before: AR_{24h} mean values, as said, reflect what was previously seen for MA_{24h}, but it is worth noting that now there is a new result. MA indexes showed that there is not a significant difference in the mean behaviors (24h or 15h) when the limbs, upper or lower, are compared between them, instead AR24h(UR,S), AR24h(UL,S) and AR24h(LR,S) show that this is no more true when the comparison is made not for the mean values of the acquisition period, but on the mean values of preponderance extracted from a synchronous epoch evaluation and compared to a common signal as the one extracted by sacrum.

While no correlation exists between AR24h(UR,S) vs AR24h(LR,S), AR24(UR,S) vs AR24h(UL,S) shows a marked linear relationship ($r = 0.83$, $p < 0.001$) (**Fig.4.16**). This may seem to respect the correlation between MA24h(UR) vs MA24h(UL) showed before, but may seem in contradiction with the high correlation previously showed between M24h(UR) and MA24h(LR). In reality this is another demonstration of the different information provided by MA and AR indexes: if a correlation exists when the average behaviors are compared for ipsilateral MA_{24h} indexes, this is not more true when their prevalences against sacrum is observed. An answer can be found in the weight that have those upper limbs activities highly independent from the lower limbs activity (i.e., upper limbs movements independent from locomotion): during the exclusively manual activities the upper limbs acceleration are more similar to those of the sacrum than are those of the lower limb always compared to sacrum, and this is reflected in a prevalence analysis; but when we observe the average global activity of an upper limb and its ipsilateral lower limb, the locomotor activity and its related accelerations (experienced by both upper and lower limbs) balance the outcomes values. So that observing average values (M24h(UR), MA24h(LR)) a linear relationship exists between an upper limb and its ipsilateral lower limb, but when a prevalence analysis against a common reference (i.e., sacrum) is done in the terms of our AR_{24h} indexes, this relationship is not more true.

Also the AR_{24h} indexes can be grouped by sex (**Fig.4.14**), in this case a t-test (**Tab.4.9**) provide a significant difference between the groups for two indexes: AR24h(UR,S) and AR24h(UL,S). As for the MA_{24h} indexes any linear relationship is detectable whether are scatterplotted the AR_{24h} indexes against age.

Table4.11, **Table4.12**, **Table4.13** and **Figure4.17** to **Figure4.21** respectively show the descriptive statistics and comparative boxplot when the AR_{24h} are computed for the three occupation-related subgroups of subjects. For what concerns AR24h(UR,UL), the results are consistent with the previous hypothesis for which this index is not dependant from macro-causes as the occupation, but more likely from personal manual habits: in fact, the p-values show that there is no significant difference among groups for AR24h(UR,UL).

5.3 MA_{15h} and AR_{15h} INDEXES

The MA_{15h} and AR_{15h} are the same indexes described and discussed before, but computed excluding the night period. In particular, it has been chosen for all subjects to delete the hours from 21:00pm to 06:00am, in accordance with what was observed in Rabuffetti [23]. This choice allows to obtain an equal reduction of all registrations (in particular the profile, including 1440 epochs for the 24h monitoring, is reduced to 860 epochs for 15 hours monitoring) avoiding differences due to the effective sleep hours of each participants; obviously it is reasonable that the threshold at 21:00pm may exclude some activities since the majority of people go actually to sleep after this time, at the same time no subjects reported particular night activities so that the exclusion of this late evening hours, consisting of typical relaxing activities (e.g., watching TV), would have not interfered with the results.

Table4.15 proposes the descriptive statistics for both the MA_{15h} and AR_{15h} indexes.

The results support an element: MA_{24h} are epoch-dependent indexes, AR_{24h} are not. Just observing the descriptive statistics is clear that MA_{24h} mean values are smaller than the corresponding MA_{15h}: the means rise in accordance with the removal of a non-active period (as is the night one), which contributes in smoothing the MA_{24h} values; this is not true for AR_{24h}. The increasing of this averaging values may not be significant, but instead the t-test results (**Tab.4.16**, **Tab4.17**) confirms what was said.

When MA_{15h} or AR_{15h} are observed separately from their 24h respective there are not particular differences concerning what was observed for the 24h indexes (e.g., age independence of the indexes etc.). The two exception are:

- *male-MA15h(UR)* vs *female-MA15h(UR)* are no more significantly different.
- AR15(UR,S) vs AR15(UL,S) are still significantly different, but with a edge p-value of 0.049.

In the MA_{24h} indexes discussion the *"female household activities"* were identified as a possible cause of the significant unbalancement between *male-MA24h(UR) vs female-MA24h(UR)*. Observing the equivalent 15h indexes the significant difference disappear so that the cause of that difference is likely present in the time period deleted from the computation. This hypothesis is consistent with an information extracted from questionnaires: women are more used to get up during night than men (71.4% of women against 21.4% of men): by change this is likely the real reason of the unbalancement; unbalancement which regard only the right limb in relation to the right-handedness of the group.

For what concerns AR15(UR,S) vs AR15(UL,S), the observed p-value increases respect the 24h indexes p-value, and, even if on the edge, it remains significant. This results show how in healthy people, even if all with a same handedness, the prevalence of an upper limb against the other is really small; in everyday activities there is a sort of homogeneity of the limbs movements against sacrum. An expectation is that the lower limbs would show an even more similar behavior than upper limbs; not having available a sensor for both ankles this point needs further investigations.

5.4 MA_e 24h PROFILES

The following figures are the examples, for two subjects, of the MA_e profiles cited in **Chapter3.6**. In particular have been chosen two subjects with opposite behaviors: the first is a student, with a common mildly daily motor activity, the second is the riding instructor, a subject particularly active as showed by his means and max values. **Figure5.1** and **Figure5.3** report MA24h(UR) vs MA24h(UL) + MA24h(UR) vs MA24h(S) for the first and second subject respectively; **Figure5.2** and **Figure5.4** report MA24h(UL) vs MA24h(S) + MA24h(LR) vs MA24h(S) for the first and second subject respectively once again.

[N.B.: the mD reported in each graph is the mean difference between the two MA_e drawn].

Table5.1 shows the indexes values for the subject PV92F, a 23 years old female, which refer **Figure5.1** and **Figure5.2**.

Tab.5.1 - MA_{24h} and AR_{24h} indexes outcomes for PV92F.

PV92F - 24h								
MA (UR)	MA (UL)	MA (S)	MA (LR)	AR (UR,UL)	AR (LR,UR)	AR (UR,S)	AR (UL,S)	AR (LR,S)
90.1	82.0	41.7	111.0	7.5	42.7	39.9	32.6	62.7

Observing the UR vs UL profiles is clear a global equivalent use of both the upper limbs: the two trends are equal during the large part of the day with a slightly prevalence of the right hand (AR(UR,UL) = 7.5%) due to handedness (Oldfield's test = 75%). In particular, the larger difference between the two upper limbs approximately highlights from 09:30am to 12:00am, time the subjects reported as a period of *"no desk work"* . This non-sedentary activity is also evident in the LR vs S graph: MA_e(LR) and MA_e(S) increase significantly respect some previous periods; a clear example of the sacrum and lower limb ability to discriminate activity from non-activity periods. When is reported a *"desk activity"* (14.15pm to 16.30pm), the UR and UL activity turns into a greater homogeneity than before, S and LR activity is more fractionated and this is likely due to brief period of locomotion.

Some others interesting points:

- 21.10pm approximately, the subject reports *"dry hair"*: a peak in UR and UL, while the activity of S and LR is really moderate, likely due to a standing position and little displacements.
- 7:55am to 9:10am and 16:35pm to 17:40, the subject reports *"drive automobile"*: moderate and similar activity for upper limbs, slightly S activity and a LR substantially absent.

Table5.2 shows the indexes values for the subject FC90M, a 26 years old male, which refer **Figure5.3** and **Figure5.4**.

Tab.5.2 - MA_{24h} and AR_{24h} indexes outcomes for FC90M.

FC90M - 24h								
MA (UR)	MA (UL)	MA (S)	MA (LR)	AR (UR,UL)	AR (LR,UR)	AR (UR,S)	AR (UL,S)	AR (LR,S)
149.3	141.5	94.4	174.4	1.0	19.7	19.5	17.9	34.4

The average values of this active subject are clearly higher. Furthermore he shows an upper limb prevalence almost perfect (AR(UR, UL) = 1.00%, and a small difference between AR(UR,S) and AR(UL,S), or anyway smaller than that showed by the previous participant), his Oldfield's test resulted 62%.

This subject was less specific than the previous in filling the diary, so that is not possible to justify some trends (e.g., the two evident peaks at 21:00pm and 23:50pm). The reason why this subject is presented is the will to show how it can present the MA_e profile of a subject not used to sedentary activity due to his occupation:

- 10:00am to 14.30pm *"no desk work"* interspersed by some brief driving periods.
- 14:30pm to 18:00pm *"actual sport activity"*, the S and LR increment is evident even compared to his previous, anyway, non-sedentary activity. .

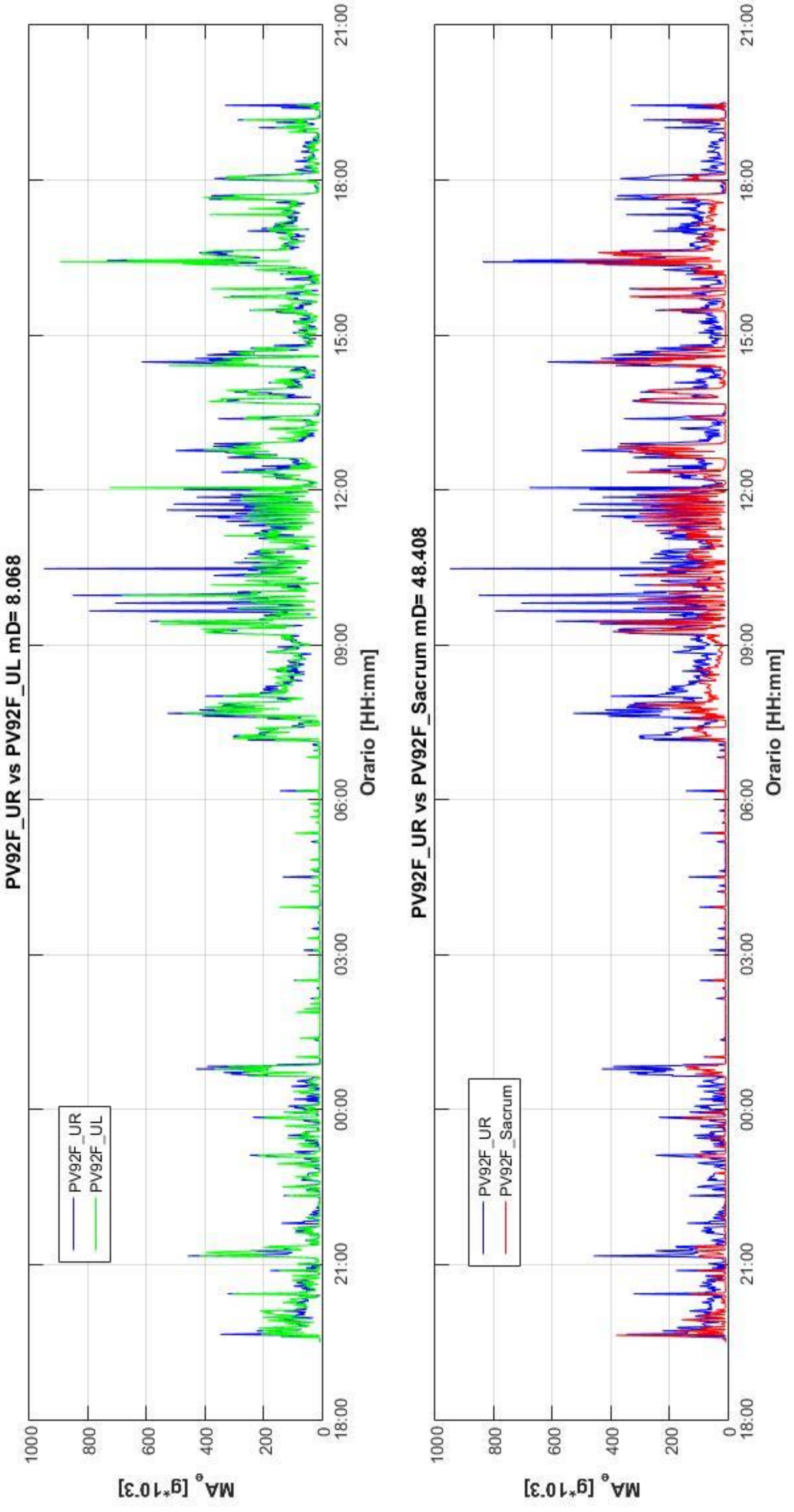

Fig. 5.1 - MA$_e$ profiles exemples MA24h(UR) vs MA24h(UL) + MA24h(UR) vs MA24h(S).

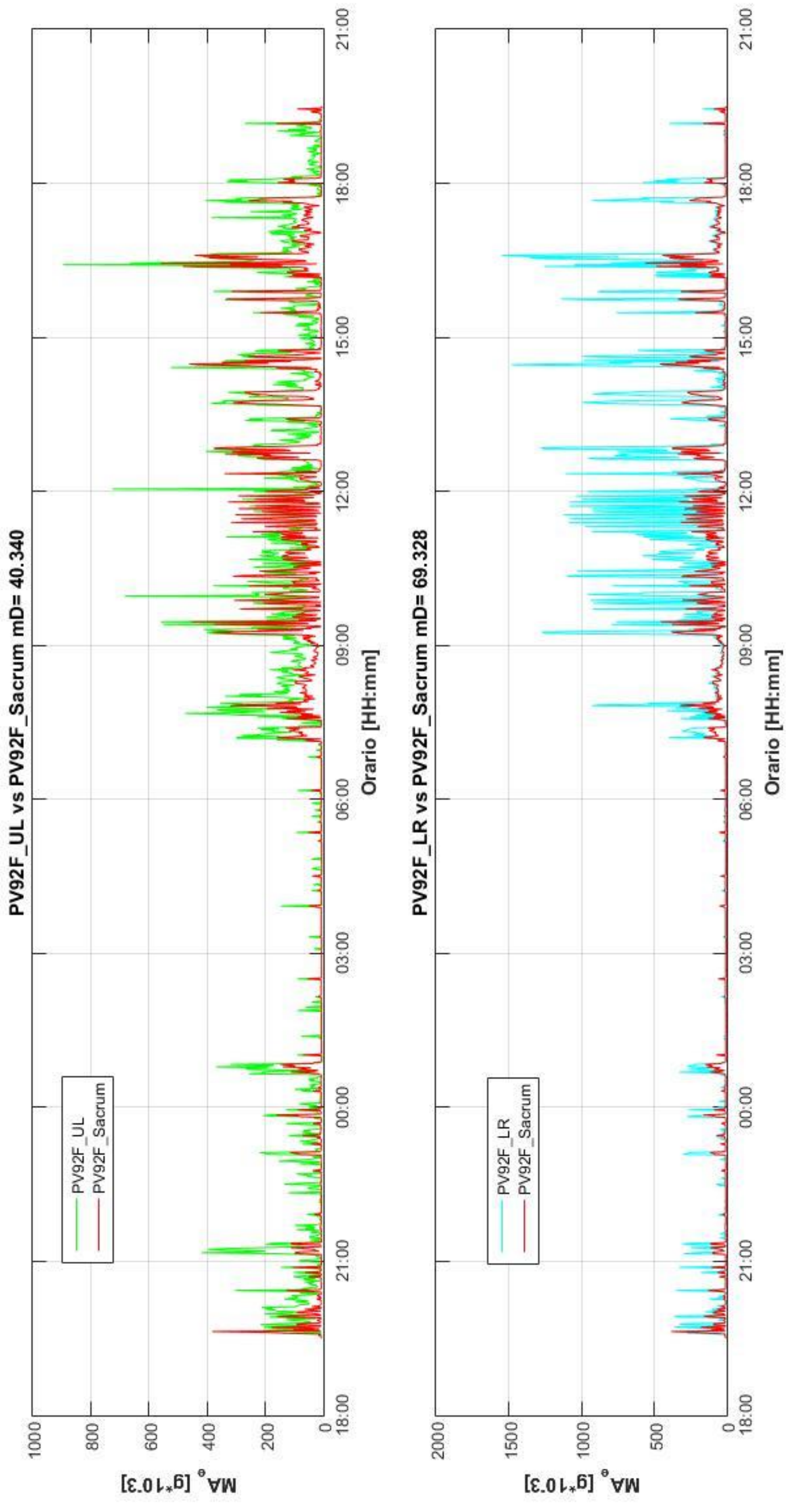

Fig. 5.2 - MA$_e$ profiles exemples MA24h(UL) vs MA24h(S) + MA24h(LR) vs MA24h(S).

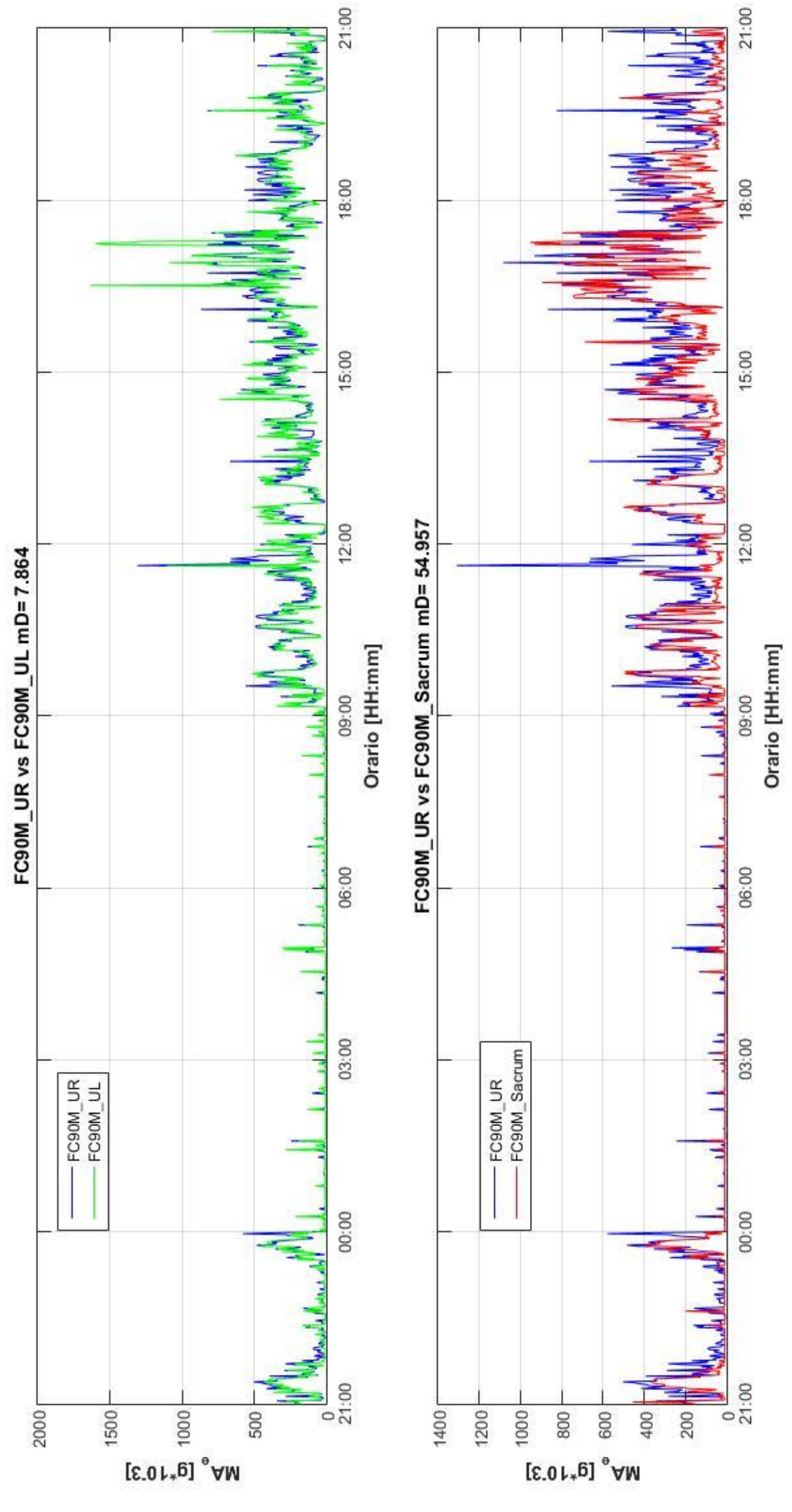

Fig. 5.3 - MA$_e$profiles exemples MA24h(UR) vs MA24h(UL) + MA24h(UR) vs MA24h(S).

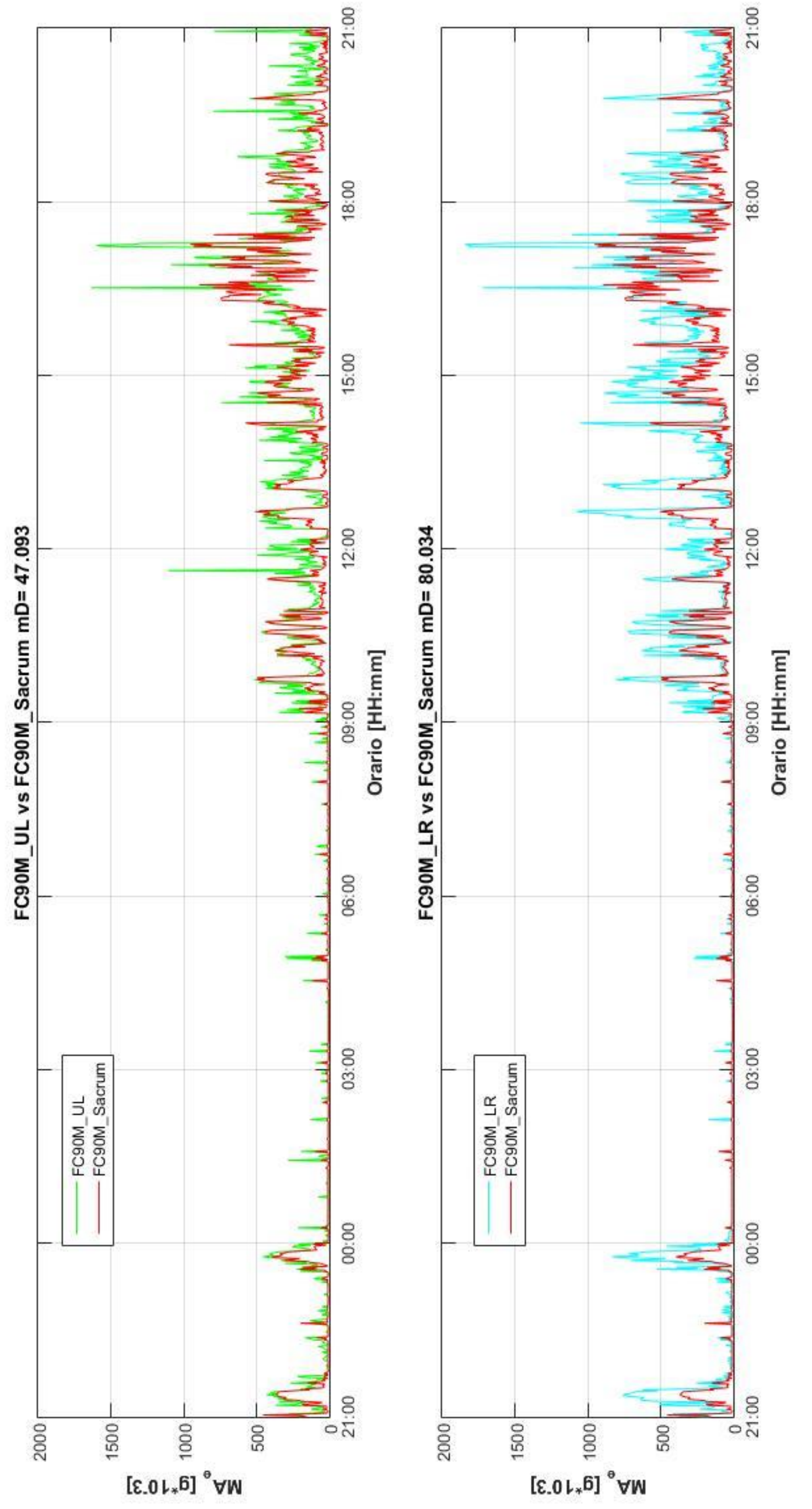

Fig. 5.4 - MA_e profiles exemples MA24h(UL) vs MA24h(S) + MA24h(LR) vs MA24h(S).

5.5 TEST-RETEST RELIABILITY

The study tried also to evaluate a test-retest reliability. The aim of this proceedings was not to test the reliability of the instrument *GENEActiv Original*, but rather the one related to the MA and AR indexes. In fact, as said in a previous chapter (**Chapter3.1**), GENEActiv is a validated instrument and studies as the one performed by Dale [4] already demonstrated its technical reliability and validity.

The retest session discussed involved 5 subjects in relation to their availability and willingness, when possible the retest session took place the same day of the week of the first acquisition: this choice should remove possible biases; clearly, acting outside of a controlled environment (e.g., a laboratory) it was not possible exclude unpredictable changes in the motor activity due to exogenous causes (e.g., the weather, occasional relationship with people, etc.) or endogenous causes (e.g., the personal mood or state of health). **Table4.18** present a summary of descriptive statistics (i.e., mean, standard deviation, max, min) in terms of the **Δ** (**test value - retest value**) for the subgroup of five subjects in the 24h.

Considering the objective variability may be present in the motor activities of a subject due to the exogenous and endogenous factors cited before, it is worth noting that the table shows differences of just few units in all five participants. The major Δs are observable in max and min, two values extremely influenced by the actual daily activities. The only body segment that proposes a good difference in the averages is LR ($\Delta = 6.2$), but this is probably due to the fact that it is the most variable point among the four and also the one which usually presents the higher values, as was explained in the discussion of MA indexes. These outcomes show how comparable can be the motor activities in different days, when are acquired people used to have a predictable motor behavior, as all those who follow a working routine during the week.

Then were computed also correlation coefficients for test vs retest considering each single index (MA or AR), the results are reported in **Table4.19**. The Pearson's r can be partially compared with those extracted by Rabuffetti et al. [23] (**Table5.3** reported below) when were used the same indexes limited to the wrists monitoring.

[N.B.: although the index are the same the experiment by Rabuffetti did not use *GENEActiv Original*, but another kind of device]

Tab. 5.3 - Pearson's r values for test-retest comparison in Rabuffetti [23].

	MA(UR)	MA(UL)	AR(UR,UL)
24h ICC	0.93	0.82	0.70

Four out of nine indexes show a good correlation, Pearson's r higher or close to 0.70: in particular, MA24h(UR) with 0.75, MA24h(UL) with 0.69, AR24h(UR,S) with 0.74 and AR24h(UL,S) with 0.81.

The outcomes by Rabuffetti appears better for each index for which a comparison is possible, at the same time this study had the possibility to use just 5 retest sessions against the 20 of Rabuffetti. In this way we can say that for the three comparable index, the outcomes of this experiment show some coherence with the results of Rabuffetti considering that his retest group is four time larger. It is reasonable to assume that expanding the retest group the r coefficients for MA(UR), MA(UL) and AR(UR,UL) would increase.

For what concerns MA_{24h} indexes the upper limbs show the higher Pearson's r values, then is MA24h(S) and last MA24h(LR): in particular, the upper limbs propose good values even with our small group. While the low value for LR can have some explanation in the high variability of movements of lower limbs, MA24h(S) is expected to show an higher value than 0.55 considering its limited variability, from this the needs of further investigations with a larger retest group.

When the AR_{24h} against sacrum are considered, AR24h(UR,S) and AR24h(UL,S) show the higher values, while, once again, the index concerning LR presents the lower value.

5.6 ACCEPTABILITY RESULTS

The good acceptability outcomes of this study recall the study of Huberty et al. [6]: Huberty highlights how a lot of studies (related to the motor activity monitoring by wearable devices) report informations concerning the choice, the protocols and the calibration of actigraphs, but few or none analyze the impact of wearable devices on subjects in terms of acceptability and feasibility of wearing them, speaking about comfort or preferred placement. Huberty tested the feasibility (i.e., acceptability, demands) of three wearable sensors widely used in research settings among which appears GENEActiv.

The results related to the experiment here discussed, summarized in **Table4.20**, confirm GENEActiv being *"easy to wear"* and *"comfortable also during sleep"* as was for Huberty. Furthermore our results underline some little issues that could be present in the case of a multi-sensor setup: in particular, involve pelvis (i.e., sacrum) and ankles could bother some subjects, but in any way the discomfort, with GENEActiv is totally acceptable. Lastly, we would highlight that none of the subjects complained about the fact that the devices does not act like watches, contrary to what was observed by Huberty; this although our participants were forced to wear a device for each wrist and so a real watch was not wearable in any way.

The answers to our questionnaire make GENEActiv highly recommended as wearable device (in terms of comfort) for the monitoring of motor activity, regardless it is required to wear it on wrists or on others body points as are ankles or waist.

5.7 CONCLUSIONS

The study here presented and discussed wants to be an example of the wearable devices potential in describing motor behaviors in free-living environments.. The importance of studying outside-laboratory motor investigations arises from a new awareness of the limits of modern rehabilitation laboratories; in particular, laboratories are expected to focus on *motor capacity*, while not assessing the *motor performance* of patients: wearable devices can complement laboratory examinations in assessing motor performance. Thanks to the miniaturization of technology and low costs, wearable devices for the monitoring of different health-related variables have become very common also among public consumers; besides these consumer products exist a set of professional tools, more reliable and of flexible usage. Our experiment used *GENEActiv Original*, a light wearable accelerometer for professional use based on MEMS technology; two elements related to GENEActiv it is worth noting are: the comfort of the device and the possibility to measure movements extracting raw acceleration data, avoiding the use of common pre-processed proprietary count units.

The experiment was designed to monitor in a as fully as possible way the whole body daily activity having available four accelerometers: the final devices setup involved the wrists, an ankle and the waist. In particular the choice was to acquire participants during a whole 24h day, including the sleep period. All the results have been extracted focusing on the use of indexes designed on purpose: the Motor Activity MA_e (and the related MA_{24h} variables) and the Activity Ratio AR_{24h} indexes.

The target of the study was not only to provide a variability profile for health subjects, but also verify the descriptive capabilities of the designed indexes, in the perspective of a monitoring of physically impaired people.

The indexes showed a valid ability of characterize healthy motor behaviors, confirming all the expectations of circumstance; the results were supported by personal participants diaries and questionnaires which provided a variety of demographic and lifestyle data.

In particular:

- The MA_{24h} highlight the high correlation existing between the limbs of an healthy subjects, in a sort of equilibrium in their usage. These mean indexes can also characterize the behaviors of each limb: it was showed that in healthy people upper limbs have very similar mean behaviors, with a slight preponderance of the limb related to the handedness.
- MA24h(S) approximates in a good way the global motor activity as showed in the comparisons between occupations or for the more active participants. Once identified some thresholds it may be used to quantify the global motor activity.
- The AR indexes allow to extract specific information of limb prevalence.
- MA_e can be used to plot MA_e profiles usable for visual comparisons of the daily activities and/or between the measured body points.
- The MA and AR indexes do not act in the same way when a large period (i.e., night/sleep period) is subtracted by the acquisition. The MA values vary significantly, this it is not the case for the AR indexes, based on synchronous comparisons.
- retest experiments were performed on a small group; an investigation on a larger group is needed.
- The MA and AR indexes do not show significant difference among genders.
- The indexes showed a independence from age in healthy subjects in the considered age range (18-58 years), thus excluding elderly: the motor performance is independent from age, daily living activities do not request or push towards movement limits, so that a 24 years man or a 50 years man can be compared in an activity tracking.
- *GENEActiv Original* is confirmed as a reliable, comfortable and practice wearable device.

5.8 FUTURE DEVELOPMENTS

The presented study is definitely perfectible. First of all, for the purposes of completeness, would be interesting to add one more sensor (up to five *GENEActiv Original*), so that both the lower limbs may be acquired as in the case of the uppers: remember that the sensor setup provides the presence of just one ankle monitored, ankle chosen in relation to the subjects' handedness. This new sensors configuration may provide indexes absolutely not computable with the current setup as MA24h(LL), AR24h(LL,UL) and AR24h(LL,S) and this would allow comparison for the lower limbs as showed for the uppers. In this case is also important to redefine the group of health participants so that would be verifiable a good (or even balanced) presence of left-handed people. Furthermore, reinforce the size (i.e., number of subjects) of the group attending the retest session should help obtaining more reliable data for the test-retest reliability of both the MA and AR motor indexes.

Another aspect that needs further investigation is certainly the one related to **MA_e** and the epoch duration; this passage is open to various options. At first may be thought a completely new epoch (larger or shorter) and analyze how it impacts on the outcomes showed. Secondly, indexes may be designed considering all new criteria different from the average values on 24h or 15h (MA_{24h}, MA_{15h}, AR_{24h} and AR_{15h}): for example, you can base the indexes no more on a priori assumptions, but on a posteriori decisions as compute the indexes only in relation to the largest level of activity or specific kind of activity. These options produce different, and possibly independent, results and therefore can be considered complementary options which quantify new different aspects.

Obviously the greater future application would be the repetition of the experiment involving moderate and/or severe physically impaired subjects: post stoke patients, subjects with asymmetric motor deficits, posture deficits etc. . The measurement sessions would be performed out of the laboratory in a daily life context, contrary to the laboratory experience this kind of patients are used to; then the results should be compared with those of healthy people and a discussion on the ability of these indexes to classify, describe and characterize some diseases should be made. Speaking about pathological subjects would be also interesting to apply the monitoring on subjects with motor-sleep-related pathologies (e.g., restless legs syndrome) and focus the acquisition only during the night period.

REFERENCES - (in alphabetic order)

-[1] Activinsights Ltd. - www.activinsights.com

-[2] Altini M, Penders J, Vullers R, Amft O. Estimating Energy Expenditure Using Body-Worn Accelerometers: a Comparison of Methods, Sensors Number and Positioning. IEEE Journal of Biomedical and Health Informatics 2014; 19(1): 219-226.

-[3] Bouten CVC, Koekkoek KTM, Verduin M, Kodde R, Janssen JD. A Triaxial Accelerometer and Portable Data Processing Unit for the Assessment of Daily Physical Activity. IEEE Transaction on biomedical engineering Vol. 44, No. 3, March 1997.

-[4] Dale WE, Rowlands AV, Hurst TL, Catt M, Murray P, Eston RG. Validation of the GENEA Accelerometer. Med. Sci. Sports Exerc. 2011; Vol. 43, No. 6, 1085–1093.

-[5] de Bruin ED, Hartmann A, Uebelhart D, Murer K, Zijlstra W. Wearable systems for monitoring mobility-related activities in older people: a systematic review. Clinical Rehabilitation 2008; 22: 878–895.

-[6] de Groot S, Nieuwenhuizena MG. Validity and reliability of measuring activities, movement intensity and energy expenditure with the DynaPort MoveMonitor. Medical Engineering & Physics 35 (2013) 1499– 1505.

-[7] de Niet M, Bussmann JB, Ribbers GM, Stam HJ. The Stroke Upper-Limb Activity Monitor: its sensitivity to measure hemiplegic upper-limb activity during daily life. Arch Phys Med Rehabil 2007;88:1121-6.

-[8] Floor-Westerdijk MJ, Schepers HM, Veltink PH, van Asseldonk EHF, Buurke JH. Use of Inertial Sensors for Ambulatory Assessment of Center-of-Mass Displacements During Walking. IEEE Transaction on Biomedical engineering 2012; Vol. 59.

-[9] Gebruers N, Truijen S, Engelborghs S, Nagels G, Brouns R, De Deyn PP. Actigraphic measurement of motor deficit in acute ischemic stroke. Cerebrovasc. Dis. 2008; 26:533–540.

-[10] Gebruers N, Vanroy C, Truijen S, Engelborghs S, De Deyn PP. Monitoring of physical activity after stroke: a systematic review of accelerometry-based measures. Arch Phys Med Rehabil 2010;91:288-97.

-[11] GENEActiv by Activinsights - www.geneactiv.org

-[12] Gupta P, Dallas T. Feature Selection and Activity Recognition System Using a Single Triaxial Accelerometer. IEEE Transaction on biomedical engineering Vol. 61, No. 6, June 2014.

-[13] Hagstomer M, Oja P, Sjostrom M. Physical Activity and Inactivity in an Adult Population Assessed by Accelerometry. Med. Sci. Sports Exerc. 2007; Vol. 39, No. 9, 1502–1508.

-[14] Huberty J, Ehlers DK, Kurka J, Ainsworth B, Buman M. Feasibility of three wearable sensors for 24 hour monitoring in middle-aged women. BMC Women's Health 2015; 15:55.

-[15] Hurd WJ, Morrow MM, Kaufman KR. Tri-axial accelerometer analysis techniques for evaluating functional use of the extremities. Journal of Electromyography and Kinesiology 2013; 23: 924–929.

-[16] WHO - International Classification of Functioning, Disability and Health (ICF). http://www.who.int/classifications/icf/en/

-[17] Janssen C, Cliff DP, Reilly JJ, Hinkley T, Jones R, Batterham M, Ekelund U, Brage S, Okely AD. Predictive Validity and Classification Accuracy of ActiGraph Energy Expenditure Equations and Cut-Points in Young Children. PLoS ONE 20123; 8(11): e79124. doi:10.1371/journal.pone.0079124

-[18] Laporte LE, Kuller LH, Kupfer DJ, McPartland RJ, Matthews G, Gaspersen C. An objective measure of physical activity for epidemiologic research. Am. J. Epidemiol. 1979; 109: 158-168.

-[19] Michielsen ME, de Niet M, Ribbers GM, Stam HJ, Bussmann JB. Evidence of a logarithmic relationship between motor capacity and actual performance in daily life of the paretic arm following stroke. Rehabil Med 2009; 41: 327–331.

-[20] Nagels G, Mariön P, Pickut BA, Timmermans L, De Deyn PP. Actigraphic evaluation of handedness. Electroencephalography and clinical Neurophysiology 1996; 101:226-232.

-[21] Natale V, Lehnkering H, Siegmund R. Handedness and circadian motor asymmetries in humans: Preliminary findings. Physiology & Behavior 100; (2010) 322–326.

-[22] Oldfield RC. The assessment and analysis of handedness: The Edinburgh Inventory. Neurospycologia, 1971; 9:97-114.

-[23] Rabuffetti M, Meriggi P, Pagliari C, Bartolomeo P, Ferrarin M. Differential actigraphy for monitoring asymmetry in upper limbs motor activities. 2016, Physiological Measurement, in press.

-[24] Reiterer V, Sauter C, Klösch G, Lalouschek W, Zeitlhofer J. Actigraphy – A Useful Tool for Motor Activity Monitoring in Stroke Patients. Eur Neurol 2008; 60:285–291.

-[25] Rinehart JK, Singleton RD, Adair JC, Sadek, Haaland KY. Arm Use After Left or Right Hemiparesis Is Influenced by Hand Preference. Stroke 2009; 40:545-550

-[26] Sadeh A, Alster J, Urbach D, Lavie P. Actigrafically based automated bedtime sleep-wake scoring: validity and clinical applications. J. Ambulatory Monitorings, 1989; 2: 209-216.

-[27] Schasfoort FC, Bussmann JBJ, Stam HJ. Ambulatory measurement of upper limb usage and mobility-related activities during normal daily life with an Upper Limb-Activity Monitor: a feasibility study. Medical & Biological Engineering & Computing 2002; 40(2):173-82.

-[28] Steins D, Dawes H, Esser P, Collett J. Wearable accelerometry-based technology capable of assessing functional activities in neurological populations in community settings: a systematic review. Journal of NeuroEngineering and Rehabilitation 2014, 11:36.

-[29] Thrane G, Emaus N, Askim T, Anke A, MD. Arm use in patients with subacute stroke monitored by accelerometry: association with motor impairment and influence on self-dependence. Rehabil Med 2011; 43: 299–304

-[30] Timmermans S, Mauck A. The Promises and Pitfalls of Evidence Based-Medicine. Health Affairs, 2005; 1:18-28.

-[31] Trampisch US, Platen P, Trampisch M, Moschny A, Thiem U, Hinrichs T. Reliability of accelerometric measurement of physical activity in older adults-the benefit of using the trimmed sum. Eur Rev Aging Phys Act (2012) 9:143–148

-[32] Uswatte G, Foo WL, BA, Olmstead H, Lopez K, Holand A, Simms LB. Ambulatory monitoring of arm movement using accelerometry: an objective measure of upper extremity rehabilitation in persons with chronic stroke. Arch Phys Med Rehabil 2005; 86:1498-501.

-[33] van den Berg-Emons RJ, Bussmann JB, Stam HJ. Accelerometry-based activity spectrum in persons with chronic physical conditions. Arch Phys Med Rehabil 2010; 91: 1856-61.

-[34] Concept Paper, WHO Guidelines on Health-Related Rehabilitation (Rehabilitation Guidelines).

-[35] World Health Organization (WHO), http://www.who.int/en/ .

-[36] Zhang S, Murray P, Zillmer, Eston RG, Catt M, Rowlands AV. Activity Classification Using the GENEA: Optimum Sampling Frequency and Number of Axes. Med. Sci. Sports Exerc. 2012; Vol. 44, No. 11, 2228–2234.