The analysis of human movement can be applied for many different purposes, from improving motion of characters in video games, interaction of robots with the environment, ergonomic devices (comfort and safety), analysis and improvement of athletes in sports, to improving diagnosis in clinical settings [21]. This thesis focuses on the assessment of human movement in the context of health. Human movement is achieved by a complex and highly coordinated interaction between bones, muscles, ligaments and joints within the musculoskeletal system under the control of the nervous system [145]. Healthy musculoskeletal and nervous systems are at the basis of efficient spatial and temporal navigation in the environment. Normal age-related deterioration, injuries or diseases of the individual components of these systems may result in problems with adequate motor control and adaptation to changing environments which can lead to instability or disability of body movements. In particular, the assessment of postural control and movement disorders are the main topics in this thesis.

Postural control. It is known that with increasing age postural control ability decreases, causing frequent falls among the population older than 60 years [84]. Falls can cause severe injuries among the older population, leading to loss of independence, and fatalities in the worst case. Exercise is considered a key aspect to improve postural control and thereby reduce the incidence of falls [48]. However, several drawbacks of exercise programs such as boring exercises, weather conditions preventing people to go outside, and cost of travelling may be the cause of low adherence rates [92]. Digital games controlled by body movements (exergames) have been proposed as a way to improve postural control because they can provide engaging elements, can be played indoors and can avoid the cost of travelling [73, 89]. However, the number of intervention programs showing the effectiveness of exergames as tools to improve postural control is still limited [120]. Moreover, further improvement of balance control assessment is still necessary [91]. The most common way to assess effectiveness of exergames to improve postural control is by assessing postural control before and after intervention programs. Assessing body movements during game-play, i.e., assessing dynamic postural control (DPC), could help increasing the effectiveness of exergames as tools to improve postural control. That is, effectiveness can increase because DPC assessment can be used to provide immediate meaningful feedback, which is a strong source of motivation [14] and because DPC assessment can be used to adjust the difficulty of exergames according to the ability of the players (another
important quality that exergames should possess [47]). However, the development of methods to assess DPC during exergaming is a challenging task and such methods are still scarce [31].

**Movement disorders** “are clinical syndromes with either an excess of movement or a paucity of voluntary and involuntary movements, unrelated to weakness or spasticity” [36]. The quantitative assessment of movement disorders can aid in monitoring the progression or deterioration of patients [156]. It can also be used to help discriminating healthy and pathological conditions such as ataxia, Parkinson’s disease, and multiple sclerosis [15, 78, 141], or between different pathological conditions that have similar clinical symptoms such as parkinsonian syndromes. An important benefit of assessing and understanding human movement is that it can help making better and more appropriate decisions regarding patient care; e.g., by adjusting therapy for patients in rehabilitation or medical care based on movement performance.

The most common methods to assess human movement in a clinical setting are clinical rating scales, which are easy to administer and have often been validated and standardized [108]. However, one of the main drawbacks of rating scales is that they depend on the evaluation and interpretation of an observer and thus contain a subjective component. Moreover, clinical rating scales are not very sensitive, making them insufficient to assess different motor control strategies during the execution of movements. For example, objective and accurate methods to assess hand movements are still scarce in clinical settings [114]. Additionally, many clinical scales suffer from ceiling effects, and the outcomes are too general to examine for instance changes in balance control in healthy older adults [13, 79].

With the development of modern tracking technology such as visible, infrared, and depth cameras, force plates and inertial measurement units (IMUs), objective and reliable analysis of human motion has become feasible. During body movement tasks, the motion can be recorded using one or more tracking devices. In general, a number of measures can be derived from the recordings such as three-dimensional (3D) trajectories, distance, velocity, and acceleration [54]. Specialized assessment of human movement is usually task-dependent. For example, assessing the smoothness of body movements can involve measures such as peak speeds, arc length, and spectral arc length (which is based on Fourier analysis), but there is no consensus regarding the best metrics to assess smoothness [10]. Assessing upper limb movement is another example that requires particular metrics such as movement time, mean velocity, maximum velocity, and target error. With the ability to collect and derive new metrics, new challenges emerge like the translation of these quantitative metrics into values with clinical interpretation, which could be used in combination with clinical rating scales [108] to reinforce current techniques of diagnosis. This combination can also improve the acceptance of novel information technology.
by physicians, as in some cases there is resistance to adopt new technology [67].

The main goal of this thesis is to develop reliable and objective methods to assess body movements for both DPC assessment in real-time during exergaming and for the assessment of movement disorders. Such methods could be valuable to improve the effectiveness of exergames and to further translate quantitative metrics into values with clinical meaning, independently of the tracking device and task. Purely quantitative metrics may not be enough to understand the infinite number of variations of human movements. Hence, visualization techniques are additionally used to perform exploratory data analysis to identify patterns and differences between groups. In general, visualization is used to gain further qualitative insight into human movement.

Firstly, in this thesis, visualization techniques are used to qualitatively analyze trajectories of the center of pressure collected by force plates during exergaming. Secondly, a method suitable to assess DPC in real-time during exergaming is presented. Subsequently, the method is applied to monitor changes over time in DPC in older adults during a six-week unsupervised intervention program. Finally, this same method to assess human movements is applied to analyze and classify movement data from patients with certain movement disorders. Assuming that the body movement trajectories are collected using one or more reliable tracking device(s), we will argue that the method developed in this thesis could be used to analyze a broad range of functional tasks such as path drawing, finger chasing, and gait performance.

The next sections of the introduction are organized as follows. Section 1.1 describes the metrics used to characterize human movements. Section 1.2 introduces the idea of using generalized linear models (GLMs) as a way to assess human performance. In section 1.3 visualization techniques are used to qualitatively assess human movement performance. Section 1.4 describes the main contributions of this thesis. Finally, section 1.5 provides an outline of the main chapters in the thesis.

1.1 Local Features of Movement Trajectories

The natural way in which healthy people perform daily functional tasks is by executing smooth movements [121]. Healthy people perform not only smoother movements but also (in normal circumstances) faster movements than patients. A smooth movement is continuous and non-intermittent, i.e., it does not intentionally start and stop at irregular intervals. Measures of the shape of a signal are considered to be valid measures of smoothness [9], whereas a common and reliable measure to assess body movements is speed.

The trajectories of body movements recorded by tracking technologies can be represented as curves in 3D space. From differential geom-
entry we know that local curvature, local torsion and instantaneous velocity provide a complete characterization of a curve in 3D space [88]. Based on [101], if a regular curve as a function of time is represented by \( \gamma(t) \) in \( \mathbb{R}^3 \), its local curvature at time \( t \) can be defined as

\[
\kappa = \frac{\|\dot{\gamma} \times \ddot{\gamma}\|}{\|\dot{\gamma}\|^3}
\]

(1.1)

where \( \times \) indicates the vector (or cross) product, \( \dot{\gamma} \) and \( \ddot{\gamma} \) denote 1st and 2nd order time derivatives, respectively, and || represents arc length. Similarly, torsion can be defined as

\[
\tau = \frac{(\dot{\gamma} \times \ddot{\gamma}) \cdot \dddot{\gamma}}{\|\dot{\gamma} \times \ddot{\gamma}\|^2}.
\]

(1.2)

To compute the local features of a curve using equations 1.1 and 1.2, the curve has to be continuous and their 1st, 2nd and 3rd order derivatives must exist. For practical purposes, as the 3D trajectories collected from tracking devices are discrete, numerical approximations are necessary. One way to approximate the curvature of a trajectory \( \gamma(t_i) \) at a given point in time \( t_i \), is by fitting a circle to the three consecutive points at times \( t_{i-1}, t_i, \) and \( t_{i+1} \). Then, the curvature value is represented by the inverse of the radius of the fitted circle [16]. This definition means that large circles correspond to small curvature values, small circles correspond to high curvature values, and straight trajectories have zero curvature. Thus, smooth trajectories should have smaller local curvature values than rough trajectories.

Instantaneous speed, turbulence intensity [94] and other local measures of the trajectories were also explored in this thesis (detailed in Chapter 2) to investigate their usefulness to assess human movement in real-time. Torsion is another local measure of a 3D trajectory that can be approximated numerically by using Taylor series expansion [154] but was not further explored in this thesis.

1.2 Generalized Linear Models

As one of the possible applications of DPC assessment in real-time is to provide immediate meaningful feedback during exergaming, multiple measures of performance such as local speed and instantaneous curvature of different body parts may produce too much information to simultaneously show on a screen. In addition, the comparison of large groups of people may be more difficult with multiple measures of performance compared to using a single measure. For practical purposes, in these circumstances, one single scalar value (measure of performance) may be better.

GLMs allow to translate multiple measures (of performance) into a single probability value \( P \) constrained between 0 and 1 [159]. Assum-
ing that high $P$ values (close to 1) represent the performance of non-
healthy people, then low $P$ values should represent the performance
of healthy people. Under these assumptions, low curvature values and
high speed values (smooth and fast) should be related to low $P$ values,
while movement trajectories with high curvature values and low speed
values should yield high $P$ values. One of the benefits of using prob-
ability values to represent movement performance is that they have a
meaningful and straightforward interpretation. Another benefit is that
the combination of local features of movement trajectories and GLMs
is suitable for the assessment of human movement in real-time. Addi-
tional details regarding the transformation of local features of move-
ment trajectories into probability values and its applications are given
in Chapters 3 and 5.

1.3 visualization

In general, visualization is the graphical representation of information.
In this sense, several disciplines have been identified. Scientific visualization is mainly concerned to understand spatial and continuous data
collected from simulations, calculations or measurements [86]. Information visualization is used to identify patterns and understand relationships between groups from abstract data [95], without considering spatial data. Software visualization has been defined as the art and science related to visualizing the structure, behaviour and evolution of software[26]. Visual analytics “is the science of analytical reasoning fa-
cilitated by interactive visual interfaces” [136].

In this thesis mainly two techniques are used, scientific and informa-
tion visualization. Scientific visualization techniques are used to repre-
sent data that were collected and derived from human movement exper-
iments, and information visualization techniques are used to identify patterns and relationships between groups of people. The types of data involved in the visualizations presented in this thesis are multivariate and categorical time series. In the following subsections the visualization techniques used in this thesis are described.

Time series plot

The time series plot is one of the most simple and most common plots
that can be visualized using ordered sequences of pairs $\langle(t_0, v_0), \ldots, (t_n, v_n)\rangle$, where $t$ represents time and $v$ represents the matching val-
ues [5]. In this thesis, time series are used to visualize discretized sig-
als derived from human movement trajectories such as speed, curva-
ture and 3D coordinates. Here, these signals are collected from different body parts such as head, shoulders, hips, and knees; and from people in different categories, such as older and younger participants.
Scatter plot and scatter plot matrix

The scatter plot is probably one of the most versatile inventions in the history of graphical data representation [40]. It has been estimated that between 70% and 80% of the scientific publications include scatter plots [138]. Scatter plots illustrate the relationship between two variables, that are represented on perpendicular axes in the plot. At the same time, scatter plots can be used to distinguish categories by color-encoding the symbols representing the categories. For each pair of values one symbol is displayed at the corresponding coordinates. Scatter plot matrices can be used to illustrate the relationship between multiple variables [20]. Nowadays, interactive 3D scatter plots are also used to explore huge amounts of information such as astronomical data [103].

Heat maps

The heat map is based on color-coded matrix representations that are more than one century old [148]. Nowadays, heat maps follow a pixel-based representation approach, which is typically a rectangular tiling of a color-coded data matrix [5]. Heat maps are used in this thesis in several ways such as to simultaneously explore several hundreds of time series, to visualize multidimensional data, to visualize movement performance, and to visualize changes in movement performance over time.

Box and violin plots

Box plots are useful to show the distribution of the data by illustrating center, spread, asymmetry and outliers [139]. In addition, violin plots can reveal peaks, valleys and bumps in the shape of distributions [58]. These features can be useful for the identification of differences between distributions. Overlapping violin plots can be used to visualize (dis)similarities between two distributions where the area of overlap [23] can be a measure of similarity between the distributions.

Parallel coordinates

The parallel coordinate plot is a visualization technique for exploratory multidimensional data analysis [63]. This technique represents each variable in the multidimensional space as a parallel axis. Then, the values of the vectors in the multidimensional space are represented as dots on the axes and connected by a polyline. There are several variations of parallel coordinates, for example, using curved lines instead of straight lines which can partially solve ambiguity. Another example is the extension of parallel coordinates into 3D space referred to as parallel glyphs [37]. Parallel coordinates and parallel glyphs have many
applications in engineering and life sciences [56]. This kind of visualization is useful to identify relationships between variables, patterns and clusters in categorical data.

1.4 CONTRIBUTIONS

This thesis introduces a novel method to assess human movement based on tracking technology and GLMs. This method is shown to be suitable to assess DPC during exergaming, opening the possibility to provide immediate feedback and to develop adaptive exergames. The method is also shown to be suitable for assessing movement of patients with coordination disorders and distinguishing healthy from pathological conditions. A probabilistic scale is proposed as a novel measure of movement performance. The local curvature of movement trajectories is highlighted as a potentially useful measure of smoothness of body movements. Several visualization methods are used to analyze movement performance. For example, overlapping violin plots in parallel are used to visualize differences between groups across multiple variables, color-encoded probability values in heat maps are used to visualize movement performance, and a combination of heat maps and time series plots are used to visualize changes in postural control performance over time.

1.5 ORGANIZATION OF THE THESIS

In Chapter 2 local features extracted from two-dimensional (2D) trajectories of the center of pressure as estimated from force plate recordings are visually explored. As a first step towards the main goal of this thesis, several visualization techniques were used such as parallel coordinates, box plots, overlapping violin plots, heat maps and scatter plot matrices, which helped identifying some of the best features to assess human movement in real-time.

In Chapter 3, a novel method to assess body movements is introduced based on probabilistic GLMs. Local curvature and instantaneous speed (two of the measures identified in Chapter 2) were used to train GLMs for distinguishing 20 older and 20 younger participants. The data were collected using Microsoft Kinect 1 during exergaming. To test the usefulness of the model to make predictions of DPC performance five-fold cross validation was used. The resulting parameters of the GLMs helped to further track changes in movement performance over time.

In Chapter 4, the estimated parameters of the best GLM (as obtained in Chapter 3) were used to assess performance in dynamic postural control during exergaming of 10 participants in a six-week intervention program. The results in this chapter encouraged us to further apply the method to analyze movement disorders.
In Chapter 5 the proposed method to assess human movements in Chapter 3 was adjusted to analyze 3D trajectories derived from the finger-to-nose task (FNT) of 70 participants, recorded with IMUs, with the aim to differentiate healthy participants from patients with a coordination disorder. The FNT is a neurological examination that assesses smooth and coordinated movements of the index finger from the tip of the nose of the participant to the tip of the examiner’s finger and back [70]. Finally, the possibility to apply the method to further analyze other functional tasks in clinical settings is discussed.

Chapter 6 contains a general discussion, suggestions for future work and conclusions.