The main aim of this thesis was to develop objective and quantitative methods to assess body movements for both DPC assessment in real-time during exergaming and for the assessment of movement disorders. The assessment of body movements during exergaming could be useful to enhance the effectiveness of exergames as tools to improve postural control among the older population. Improving postural control could prevent falls, which are known to occur more often with age. The objective assessment of movement disorders can be useful to aid in clinical decision making, thereby improving medical care or rehabilitation.

There is a huge number of metrics that can be derived from quantified human movement, where each metric has its own purpose and is typically applied for a particular task. However, with the exception of speed, general metrics that can be used to assess any kind of human movement are scarce. In Chapter 2, visualization techniques were used to explore promising metrics for assessing human movement in real-time using data collected from force plates. Local curvature, instantaneous speed and turbulence intensity were found to be some of the most promising measures for the assessment of human movement in general. Additionally, these measures were found to be able to differentiate movements of older and younger people. Moreover, we found that curvature could potentially be used as a measure of the smoothness of body movements. By definition, curvature measures the shape of the trajectory, low curvature values suggest smoother trajectories than high curvature values. Naturally, smoother movements are expected for healthy people compared to patients, or for younger people compared to older people. This expectation was first visually confirmed in this thesis using overlapping violin plots of curvature values showing differences between older and younger participants. The quantification of smoothness of body movements is potentially important in medicine to assess patients with movement disorders and in rehabilitation. Because these measures can be estimated locally (over small sections of the movement trajectory) they can be determined and used in real-time and can also be estimated from any kind of movement collected by a reliable tracking device.

From a human-computer interaction point of view, providing multiple measures of movement performance as real-time feedback during exergaming might be excessive and might cause cognitive overload [77]. In Chapter 3 a probabilistic measure, estimated as a function of some of the most promising local features determined in Chapter 2, was proposed as a way to assess the human movement performance using data collected from an infrared depth camera. As a single measure can be
interpreted faster than multiple measures, it is more suitable for real
time feedback during exergaming. It is important to provide a meaning
to probability values. Here, probability values were found to be suitable
for assessing performance during exergaming in older and younger par-
ticipants. Values close to 0 suggested performance as a younger partic-
ipant and values close to 1 suggested performance as an older partici-
 pant. In addition, probability values were used to distinguish older and
younger participants during exergaming with more than 85% accuracy,
using five-fold cross-validation. The ability to differentiate older and
younger participants using probabilistic scores suggested that the same
technique might be applied to distinguish patients with a movement
disorder from controls, which was further explored in Chapter 4.

In Chapter 4, the assessment method developed in Chapter 3, was
first used to monitor dynamic postural control of participants during
an unsupervised six-week intervention program. With this method, ad-
ditional evidence of the effectiveness of exergames as tools to improve
postural control was provided. Additionally, the fact that the method is
unsupervised and the assessment of body movements can be done auto-
matically are key points to motivate older people to train postural con-
trol using exergames, as they can then play the game at home while still
receiving appropriate feedback, not only in terms of gaming scores but
also in terms of meaningful body movement performance. This means
that individuals can track their own body movement performance over
time and take the appropriate actions. This finding suggests that the
method could also be used to monitor disease progression in patients
with movement disorders or to assess improvements in patients reha-
bitating from an injury or stroke, for example.

In Chapter 5, the method developed in Chapter 3 was applied to as-
 sess movement of patients with different coordination disorders with
the purpose of distinguishing them from controls using data collected
from IMUs. We showed that the method could be used to classify pa-
tients and healthy controls who were executing the finger-to-nose test
with 84% accuracy. Thus, additional evidence of the usefulness of the
developed method was presented.

6.1 LIMITATIONS AND FUTURE OUTLOOK

Most studies in this thesis only explored local curvature and instanta-
neous speed to assess human movements. Other local metrics such as
torsion and the derivatives of curvature, torsion and speed remained un-
explored, at least in the areas of exergaming and coordination disorders.
While curvature measures how much a curve deviates from a straight
line in a plane, torsion measures how much a curve deviates from a
plane, i.e., torsion is measured in 3D space, as in a spiral, and curves
on a plane (like a circle) have zero torsion. It would be interesting to
investigate, for example, what local torsion can add to the analysis of
movement in patients with movement disorders like ataxia, essential tremor or Parkinson’s disease.

One of the limitations of the presented method is that it can only distinguish between two classes of participants. In a similar probabilistic approach, one of the techniques to distinguish between three or more categories is called multinomial regression [44]. However, this technique is effective only if the predictors (features) show significant differences between groups. In this sense, speed and curvature might not be enough, as two different coordination diseases can exhibit similar speed and curvature values. Feature selection is one of the most important steps in the analysis of coordination disorders. In [83], 14 FNT features were used to differentiate DCD, EOA and healthy participants. However, 26% of the DCD participants were classified as EOA and 43% were classified as healthy. Thus, the discovery of novel features to characterize coordination diseases could be a challenging and interesting topic for future work.

As modern tracking devices have the ability to collect a huge amount of data in relatively short periods of time, another challenge concerns not only data storage and management but also the exploration of these huge datasets. Appropriate data management and exploratory visualization tools can be valuable for researchers to gain quick insight into the data, providing directions for further data exploration and analysis. The implementation of an interactive tool to generate the visualizations presented in this thesis such as violin plots (Figures 2.4 and 5.5), overlapping violin plots (Figures 2.6 and 3.3), time series heat maps (Figures 2.3 and 3.8), and heat maps showing the fit of the models (Figure 3.5) can be highly valuable for further exploration and understanding of human movements, which in turn might lead to new findings.

The motivation to assess postural control in real-time was the possibility to provide immediate feedback and to adjust the difficulty level according to the skills of the player. However, assessing human movement in real-time is just the first step in the complex process of providing feedback during exergaming. During the implementation of real-time feedback many decisions should be made such as whether feedback should be visual, auditory or a combination of both; sustained or cumulative [77]; positive or negative [14]. Thus, several research questions can be asked, such as: ‘which is the preferred method for delivering feedback during exergaming? [77]. How often should feedback be delivered? What is the effect of performance feedback on motivation and game-play? What is the relation between exercise performance and game performance (points, coins or medals)?’

Automatic adjustment of difficulty level during exergaming is another challenge. To achieve this, several questions need to answered such as: ‘is it possible to predict fatigue based on movement performance and time of game-play? Is there any association between the probabilistic performance measure and heart-rate over time? How can
exercise recommendations be adapted to exergames? What is the effect of automatic adjustment of difficulty on game flow? Commonly, exergames do not provide mechanisms to assess the appropriate level of exertion [140]. Thus, a question is how to adequately adapt the level of exertion for each player during unsupervised home exergaming. A possible direction, as suggested by [140], is using the Borg scale [12] as input of perceived exertion to the exergame in combination with the recommendations of the World Health Organization [93]. Some of the recommendations concern the intensity of physical activity, muscle-strengthening, or aerobic and anaerobic activity. Another interesting approach is to adjust the difficulty level based on the recognition of facial expressions in combination with movement performance [151], as fatigue may be reflected in facial expressions during exergaming.

The techniques used in this thesis were applied to distinguish movements of older and younger people, and of healthy participants and patients. Another application could be to investigate the sensitivity of these techniques for assessing the performance of elite athletes, where a small change that improves their performance can be the difference between winning or losing a competition. Not only quantifying but also visualizing those small changes could be extremely valuable for coaches and athletes.

6.2 CONCLUSION

This thesis has explored the assessment and visualization of a tiny part of the infinite universe of human movements. The contributions of this thesis are promising for further assessing and understanding human movements. Local measures of the movement trajectory were shown to be important for the assessment of human movement in real-time. Novel visualizations have been presented to understand human movement performance. Probabilistic models were proposed as a novel way to assess human movements. Finally, it was shown that the methods presented in this thesis are useful to assess human movement across different tasks and across different tracking devices.