① Understanding how individuals move could be useful for identification, say in security applications, or for determining the quality of a movement, say for rehabilitation.

② This can mean that the subtle signatures of each individual's movement could be missed.

Chapter 1

Introduction

1.1 Background

Human movement involves ~~is~~ a complex system which involves ~~where~~ not only multiple joints and limbs ~~are involved~~ for a specific task in a determined environment but also ~~how we process the~~ external information processed through ~~with~~ all of our available senses and ~~use~~ our prior experiences, which all play a crucial role in the way each person moves. ① Recent studies in human motion recognition have revealed the possibility to estimate features from lower dimensions signals to distinguish differences between styles of movement, such as pedalling ~~motion~~ Quintana-Duque (2012, 2016), or ~~to perform~~ gait ~~identification~~ Frank et al. (2010); Samà et al. (2013) ~~or to do pattern recognition from biological signals Gómez-García et al. (2014)~~.

The lower dimension signals from biological signals are generally time series of one ~~1~~–dimension in $\mathbb{R}$ which commonly have high nonlinearity, complexity, and non-stationarity (Gómez-García et al., 2014). ~~where~~ Traditional methods, in time-domain or frequency-domain, tend to fail to detect tiny modulations in frequency or phase (Marwan, 2011). ② However, methods of nonlinear time series analysis can ~~objectively~~ quantify such human movement variability (Frank et al., 2010; Gómez-García et al. 2014; Marwan 2011; Packard et al. 1980; Quintana-Duque 2012, 2016; Samà et al. (2013); Stergiou and Decker (2011). With this in mind, Bradley and Kantz (2015) reviewed methods for nonlinear time series analysis, such as ~~which provide the foundations to~~ reconstruction of the state space ~~methodology~~ (RSS) (Takens, 1981), recurrence plots (RP) (Eckmann et al., 1987), recurrence quantification analysis (RQA) (Zbilut and Webber, 1992) ~~and others~~. Such methodologies are implemented ~~very easily~~ using embedding paramters (m and τ) which are explained below. However, the computation of embedding parameters is still an open problem since there ~~are~~ ~~is~~ is no general technique to compute the embedding parameters becuase time series are system-dependent, meaning that these may only work for one purpose (e.g., prediction), and may not work well for another purpose (e.g., computing dynamical invariants) (Bradley and Kantz (2015).

(sorry)

In addition, the quality of the time series data affects reliability of ~~is important to have reliable~~ results. For instance, methodologies to compute embedding parameters e.g., autocorrelation, mutual information, and nearest neighbour, require data which are ~~is~~ well sampled and with little noise (Garland et al., 2016) or have ~~need~~ purely deterministic signals (Kantz and Schreiber, 2003). Similarly, methodologies such as RSS, RP and RQA can break down when ~~with real-world~~ datasets ~~which~~ have ~~generally~~ different length, different values of accuracy and precision (Frank et al., 2010), or ~~and~~ data is ~~may be~~ contaminated with different or unknown sources of noise (Garland et al., 2016). It is surprising that ~~even~~ despite these problems arising from ~~with the previous constraints with regard to~~ the quality of data, and ~~the problem with the~~ estimation of embedding parameters, ~~the results of analysis using~~ nonlinear dynamics have proven to be helpful to understand and characterise time series (Bradley and Kantz, 2015; Frank et al., 2010; Gómez-García et al., 2014; Marwan, 2011; Quintana-Duque, 2012, 2016; Samà et al., 2013; Stergiou and Decker, 2011).

Isn't this list identical to the one at the top of the page?

New paragraph

Another point to consider when analysing ~~with~~ time series analysis using nonlinear dynamics is the appropriate use of post-processing techniques such as interpolation, filtering or normalisation. ~~It~~ However,

~~can then be said that~~ there is little research ~~and understanding~~ on the effects ~~for~~ Of post-processing techniques in the interpretation of RSSs, RPs and ~~metrics of~~ RQA.

1.2 Research questions and contributions

This thesis explores the effects on RSSs, RPs and ~~metrics of~~ RQA ~~with~~ Of different features of time series such as structure, levels of smoothness and window lengths. To do such exploration, ~~we conducted~~ an experiment was conducted with twenty right-handed, neurotypical ~~healthy~~ participants in the context of human-humanoid imitation, ~~activities~~ where participants were asked to imitate simple arm movements performed by a humanoid robot. Participants and humanoid robot worn inertial sensors that collected time series. Hence, the following research questions are investigated: You say 23 on page 43

- What are the effects on RSSs, RPs, and RQA metrics for different embedding parameters, different recurrence thresholds and different characteristics of time series (window length, smoothness of the signal, structure)?
- How much smoothing of the raw signal is appropriate in order to capture the nature of the variability?
- How sensitive or robust are RQA metrics to quantify movement variability?

→ You should ~~start~~ move section 2.1 → to here because it helps explain the questions and introduces the research and prior work.

1.3 Structure of this thesis

This thesis is organised as follow. Section 2 presents a review of the state space reconstruction that includes an explanation for uniform time delay embedding and a description of the techniques to estimate of minimum embedding parameters (e.g. false nearest neighbour and average mutual information). Section 3 presents an introduction to Recurrence Plots, structures of Recurrence Plots and different metrics to perform

Recurrence Quantification Analysis. In section 4, an experiment in the context of human-robot imitation activities is presented where description of participants, data collection from inertial measurement unit sensors, and preprocessing techniques (e.g raw data, normalised data, smoothed data and windowing) are given. In section 5, results for RSS, RP and RQA are presented understand movement variability both between participants and activities, as well as the variation of smoothness of the time series. The research is finalised in conclusion and future work.

1.4 Publications

Partial work of this thesis has been published in the following peer-reviewed conferences.

- Xochicale M., Baber C., and Oussalah M., Understanding Movement Variability of Simplistic Gestures Using an Inertial Sensor, in Proceedings of the 5th ACM International Symposium on Pervasive Displays, Oulu, Finland, June 2016, pages 239–240.

This belongs before the Introduction and should include a statement of contribution

- Xochicale M., Baber C., and Oussalah M., Analysis of the Movement Variability in Dance Activities Using Wearable Sensors, in Wearable Robotics: Challenges and Trends, Segovia, Spain, October 2016, pages 149–154.

- Xochicale M., Baber C., and Oussalah M., Towards the Quantification of Human-Robot Imitation Using Wearable Inertial Sensors, in Proceedings of the Companion of the 2017 ACM/IEEE International Conference on Human-Robot Interaction, Vienna, Austria, March 2017, pages 327–328.

- Xochicale M., and Baber C., Towards the Analysis of Movement Variability in Human-Humanoid Imitation Activities, in Proceedings of the 5th International Conference on Human Agent Interaction, Bielefeld, Germany, October 2017, pages 371–374.

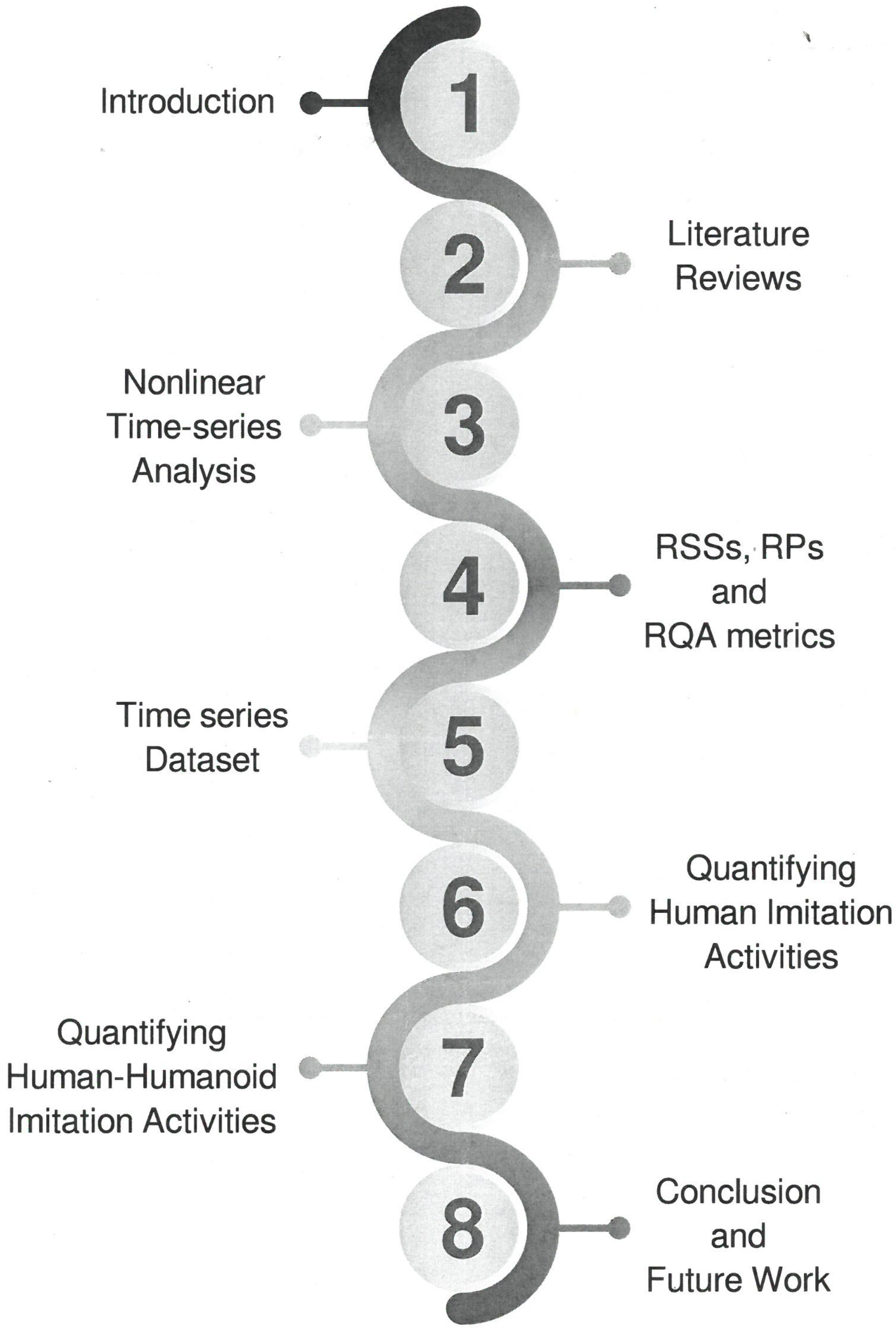

Fig. 1.1 **Thesis structure.** One to eight numbers represent the chapter number.

~~Chapter 2~~

~~Literature Reviews~~

should be kept in Chapter 1

1.3 ~~2.1~~ Movement Variability

All references need to be in Harvard style

Variability is inherent within and between all biological systems (Newell and Corcos, ~~(~~1993). For instance, variability has been studied in the ~~analysis of the~~ electroencephalographic signals in human brains (Klonowski, ~~(~~2007), in physiological signals like the heart rate variability Rajendra Acharya et al. (2006); Schumacher (2004), respiratory patterns of rats Dhingra et al. (2011), in speech variability where not only the linguistic aspect is ~~are~~ investigated but factors like gender, age, social, state of health, emotional state are strongly related to uniqueness of the speaker Benzeghiba et al. (2007) or even variability of responses to odors based on culture and gender Ferdenzi et al. (2013). Variability has also been well studied in human body movement, where for instance, Bernstein (1967) stated that no human movement is repeated exactly with the same trajectory. Henceforth, movement variability has been used as a model of fatigue to prevent chronic musculetical disorders (e.g., Mathiassen (2006); Srinivasan and Mathiassen (2012), Also, movement variability is ~~also~~ considered as an indicator of skilled performance in sport science where, for instance, Wagner et al. (2012) show how ~~analysed the~~ decrease ~~of~~ movement variability raises with skill for ~~based on statistical analysis for~~

three ~~skills~~ levels of throwing techniques (low-skilled, skilled, and high-skilled). ~~Seifert et al. (2011) modelled movement variability using hierarchical clustering analysis for competitive and recreational swimmers~~. Therefore, movement variability is ubiquitous across sports (javelin throwing, basketball shooting or running) Bartlett et al. (2007). Another interesting example is that movement variability can be considered as a identifier for personal trait Sandlund et al. (2017) where many factors of the human body can be considered, such as: age Krüger et al. (2013); MacDonald et al. (2006); Vaillancourt and Newell (2003), gender Svendsen and Madeleine (2010), pain status Madeleine et al. (2008); Sandlund et al. (2008), body composition Chiari et al. (2002), work experience Madeleine and Madsen (2009), pace, movement direction or cognitive demands like perception, memory or capacity of introspection Kanai and Rees (2011); Srinivasan and Mathiassen (2012). Additionally, Bartlett et al. (2007) highlighted that movement variability can ~~be seen~~ interpreted from different ~~angles~~ theoretical disciplines: for instance, a cognitive control theorist considere~~d~~s variability as undesirable noise and variability is reduced as ~~the~~ skill ~~performance is~~ increas~~ing~~es, meaning that "becoming dexterous freezes unwanted degrees of freedom in the kinematic chain". In contrast, an ecological motor control specialist considers movement variability as a functional role in human movement for "coordination change and flexibility to adapt" in different environments or movement variability is ~~considered as~~ the exploration and exploitation of ~~body part of~~ the "perceptual-motor workspace" Herzfeld and Shadmehr (2014); Wu et al. (2014).

cited later

if you are quoting someone, you should provide page number.

With regard to the evaluation of healthiness, Stergiou and Decker (2011) highlighted that an optimal state of movement variability is associated with healthiness. Similarly, motor disabilities are associated with either wide range of behaviours such as random, unfocussed and unpredictable or narrow range of behaviours e.g, rigid, inflexible and predictable. For instance, postural sway variability was larger for patients with Parkinson disease or variability in step width in elderly individuals where too little or too much steep width variability is associated with higher likelihood of falling. Additionally, Stergiou and Decker (2011) reviewed works that quantify movement variability in medicine, such as: variability of hearth rhythms with hearth attacks, heart rate irregularities, cardiac death syndrome, blood pressure control, brain ischemia, epileptic seizure, among many others.

2.2 Human Movement Variability

The human body movement ~~variability is~~ involves a complex system where many sensorimotor variables such as joints, muscles, nervous system, motor unit and cells are the sources for different types of variability Newell and Corcos (1993). Hence, variability encompasses different types, sources and views of variability. For instance, from a biomechanical view, motion variability ~~is~~ can be modelled as system of differential equations for the nuero-musculoskeletal control system where motion variations can occur because of "perturbations of initial states of the skeletal", perturbations of "muscular or neural subsystems ", or "external torques and forces acting on the skeletal system" Hatze (1986). According to Hatze (1986) motion variability can be caused by (a) direct consequences of adaptive learning process, (b) random fluctuation which are the result of stochastic processes in the nervous system.

Recently, Preatoni (2007); Preatoni et al. (2010, 2013) reported that inter-trial variability is defined as combination of error V_e in the neuro-motor-skeletal system with the associated nonlinear changes V_{nl}, therefore the total variability is defined as $V_{tol} = V_e + V_{nl}$ and it "may reveal the effects of adaptation, pathologies and skills learning". Similarly as Hatze (1986) and Herzfeld and Shadmehr (2014); Wu et al. (2014), Preatoni et al. (2013) considered that V_{nl} "may be interpreted as the flexibility of the system to explore different strategies to find the most effective one among the many available". Additionally, Preatoni et al. (2013) stated that part of movement

So if you talk of 'error' what is this with reference to? What is the non error signal? How is V_e actually specified/measured? What does V_{nl} mean and how is it measured?

so-this say Ve is made up of different components but how are these measured?

variability is due to error $V_e = V_{eb} + V_{ee} + V_{em}$ which is composed by an addition of V_{eb} "error in the sensory information and in the motor output commands", V_{ee} "changes in the environmental conditions" and V_{em} "changes in measuring and data processing procedures".

What I don't see from this is an explanation of how Variability is modelled & measured here

Another approach to model variability has been proposed by Müller and Sternad (2004), who~~m~~ ~~proposed a model that~~ decomposed variability into ~~exploration of~~ task tolerance(T), noise reduction(N), and covariation(C). Müller and Sternad (2004) considered that the quality of performance in goal-oriented tasks, e.g. hitting a target, is defined "by the accuracy and replicability of the results (deviations from the target) over repeated attempts of execution (configuration of join angles with its velocity, angles and position). Hence, Müller and Sternad (2004) concluded that T and N contribute more to improvement of a performance of a task than C for initial practice, meaning that a new combination of angles and velocities explore a large region of solution space (hitting the target). However, for later practice, T diminished and N and C started to be more relevant. Also, Müller and Sternad (2004) showed in various experiments of throwing actions that variability in the movement results (deviations from the target) is generally smaller than variability in the execution (variables or release angles and velocities) for which it is concluded that covariation between execution variables is another component of variability. With that in mind, Müller and Sternad (2004) concluded that task space exploration is an essential contribution to the improvement of movement performances which is an explain to the noise increase in early practice phases as explained by Newell and Corcos (1993) where variability is part of the exploitation of the workspace.

It would be useful to give an example here to show how the parameters are measured and how they interact with each other

~~Moreover,~~ Seifert et al. (2011) ~~conducted experiments with~~ applied hierarchical clustering to data from competitive and recreational swimmers, ~~to~~ and concluded that non-expert(recreational swimmers) ~~whom~~ "seek an individual coordination pattern to accommodate the novel constrains of locomotion in

So how do the two approaches differ and (more importantly) what are they missing?

water" and experts ~~whom after a considerable practice movement variability~~ have a narrower range of movement solutions. However, it is predicted that elite swimmers will explore the environments to optimise their technique which create another secondary blooming of variability. Seifert et al. (2011) also mentioned that inter-individual coordination variability could be the result of (i) different state of process learning, (ii) environmental constraints (different perception of the aquatic resistance), or (iii) different perception of the task constrains (floating instead of swimming).

what do you mean ?

So, this discussion needs a definition (in maths) of what is variability and what affects it

However, further research requires to be done to quantify variability where Newell and Slifkin (1998) stated that movement variability can be considered as "an emergent property of determinism, stochastic, and even singular processes in an evolving nonstationary dynamical system" and Stergiou and Decker (2011) pointed out that nonlinear measurement tools revealed that is not the magnitude that is important but the structure of movement variability that helps to understand human-perceptual-motor functioning which led us to the next section of measurements of variability.

good - and why would nonlinear dynamics be appropriate?

2.2.1 Measures of Variability

Measuring movement variability represent s ~~also~~ a challenge where for instance traditional approaches in statistics or frequency domain tend to fail when measuring different types and sources of variability.

This is a bad sentence that has the end repeat the start

~~For example,~~ Hatze (1986) proposed a measure of dispersion to quantify the deviation of motion from a certain reference using the Fourier series. In this ~~however such~~ approach, deviations are ~~came~~ from angular coordinates (radians) and linear coordinates (meters) which is an unaceptable fusion of variables. Hence, Hatze (1986) proposed the use of transentropy as a ~~which is~~ global quantifier for motion variability which ~~and~~ is able to measure dispertion considering that any movement deviation on a body join may be the result of deterministic and stochastic causes. Transentropy, as a mesuremente of motion

Explain the formula and why this is unacceptable.

So entropy sounds to me like a measure of the stability of a signal? I guess Hatze says anything that changes with time can be shown to be stable? But you don't say why he calls it 'transentropy' or what it is or how it is defined.

You don't explain the difference between stability and variability or what entropy is intended to measure.

variabilty, is fundamental to compute other metrics such as average transentropy, weighted global transentropy or time transentropy.

Vaillancourt et al. (2001) pointed out that it's rare for ~~no difference of~~ frequency and amplitude ~~is presented~~ to differ in postural tremor of patients with Parkinson's disease but differences in time-dependent structures are apparent, and ~~Such changes of time-dependent structures with no differences in amplitude and frequency of tremor are~~ associated with a change of regularity of postural tremor. Therefore, Vaillancourt et al. (2001) considered appreciate ? entropy (ApEn) to quantify such regularity in time-dependent structures. How?

Of course it is - because these are just variations of the measure. Why is this useful to say?

Preatoni et al. (2010) pointed out that subtle changes in the neuromuscular system are caused by influences of environmental changes, training procedures or latent pathologies. Measuring such variables with conventional statistics (e.g. standard deviation, coefficient of variation, intra-class correlation coefficient) is only for overall variability. Therefore, using nonlinear dynamics tools such as sample entropy (SampEn) and approximate entropy (ApEn) can help to analyse the deterministic and stochastic origin of movement variability. Recently, Preatoni et al. (2013) investigated that movement variability is considered as a compensation of noise in the neuro-musculo-skeletal system and the exploration of different strategies of movements to find the most appropriate pattern for the actual task. Such compensation of noise and adaptation of movements cannot be quantified entirely with the use of conventional approaches for which non only the use of entropy measures (SampEn and ApEn) but Lyapunov exponent Abarbanel et al. (1993); Smith et al. (2010).

So - what you do here is name approaches without (a) explaining them or (b) critiquing them. If you intend to describe in more depth in a later chapter, say so. Also, explain why these approaches are necessary for your thesis.

2.3 Human-Robot Movement Variability (HRMV)

2.3.1 HRMV in rehabilitation

Movement variability in the context of human-humanoid interaction has also been reported but not investigated in detail. For example, Guneysu et al. (2014) studied automatic evaluation of upper body actions with eight healthy children mimicked NAO, an humanoid robot and with the use of a Kinect sensor to get data of join angles of the participants' skeleton. To evaluate ~~the~~ motion imitation, Guneysu et al. (2014) evaluated similarity error, which is low for high~~t~~ similarly, using Dynamic Time Warping(DTW) ~~which~~ penalising large ~~amount of~~ angle errors over ~~and tolerate angles which are~~ ten percent in the area range of the motion type. Also recall measure, ~~which is hight for hight similarity~~, represents "how much of angular area covered by baseline motion is also covered by the child's motion in the selected frame window." Then, Guneysu et al. (2014) reported physiotherapist's evaluation using Intraclass correlation coefficient (ICC) which a metric for reliability of ratings. However, it it interesting to note that the proposed metrics of similarity error and recall measure with the ICC metric are not totally reliable since they did not model complex movements (involvement of multiple joins). Recently, Guneysu et al. (2015) presented variation of four physiotherapists ~~movements~~ performing five actions repeated ten times each which were quantified using basic statistical features (sample mean and sample variance). However, Guneysu et al. (2015) found~~ed~~ that initial positions of arms changed from person to person, specially for the key turning action. Additionally, different the structures of time series were presented from each of the physiotherapist, where for instance, Therapist 2 performed the activity at half amplitude compared to the others.

Why did they do this study?

What were the results?

What actions?

Görer et al. (2013) conducted an experiment for a robotic fitness coach where eight participants performed five gestures (three for arm related exercises and two for leg strength exercises). However, it is not clear how the evaluation of synchronisation of human's and robot's movements with a gold standard movement performed by the robot was performed since only graphical visualisation is presented. With that, it was stated that only one subject out of eight fail to imitate the gestures correctly.

— so - the studies done to data have used small samples and had incomplete analysis, what do they tell us?

2.3.2 HRMV in robotic dance

Human-robot movement variability can also be seen in robotic dance activities. For example, Tsuchida et al. (2013) explored four dance formations which were performed three times by nine participants whom had three years of experience: dancing with a robot, dancing alone, dancing with a self-propelled robot and dancing with a projected video. Two participant's movement positions were presented using twelve trajectories per participant of z and x directions for four dance activities in three trials. Although, the dance experiment was very rich in terms of movement variability for participants, only distance between each of the conditions in the dance formation was considered to conclude that the sense of dancing with a projected video of a person were the closest to dance with a real person and the trajectory of dance with a self-propelled robot were the closest to the trajectory of a dancer. It is not very clear why the distribution of trajectories for subject 1 were more uniform than the trajectories of subject 2.

explain in more detail

it would be good to know more about the data

2.4 Gaps in the study of Movement Variability in the context of Human-Humanoid Interaction

Even though with the previous investigation in movement variability little research has been done with regard to the conditions of the signals (e.g. window length, post-processing techniques, noise contamination, nonstationarity, etc) to produce reliable results using different methods to quantify movement variability.

so - how will your thesis fill these gaps?