ARTICLE IN PRESS

Journal of Biomechanics xxx (xxxx) xxx

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech

The physiological, in-vitro simulation of daily activities in the intervertebral disc using a load Informed kinematic evaluation (LIKE) protocol

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A R T I C L E I N F O

Keywords:
Spine biomechanics
Bioreactor
Physiological loading
Six-axis
Intervertebral disc

A B S T R A C T

Current spinal testing protocols generally adopt pure moments combined with axial compression. However, daily activities involve multi-axis loads, and multi-axis loading has been shown to impact intervertebral disc (IVD) cell viability. Therefore, integrating in-vivo load data with spine simulators is critical to understand how loading affects the IVD, but doing so is challenging due to load coupling and variable load rates. This study addresses these challenges through the Load Informed Kinematic Evaluation (LIKE) protocol, which was evaluated using the root mean squared error (RMSE) between desired and actual loads in each axis. Stage 1 involves obtaining the kinematics from six-axis load control tests replicating 20 Orthoload activities at a reduced test speed. Stage 2 applies these kinematics in five axes, with axial compression applied in load control, at the reduced speed and at the physiological test rate. Stage 3 enables long-term tests through six-axis kinematic control combined with diurnal height correction to account for the natural height fluctuations of the IVD. Stage 1 yielded RMSEs within twice the load cell noise floor. Low RMSEs were maintained during stage 2 at reduced speed (Tx:0.80 ± 0.30 N; Ty:0.77 ± 0.29 N; Tz:1.79 ± 0.50 N; Rx:0.02 ± 0.01Nm; Ry:0.02 ± 0.01Nm; and Rz:0.02 ± 0.01Nm) and at the physiological test rate (Tx:3.45 ± 1.81 N; Ty:3.82 ± 1.99 N; Tz:11.32 ± 8.69 N; Rx:0.13 ± 0.07Nm; Ry:0.16 ± 0.11Nm; and Rz:0.07 ± 0.04Nm). To address unwanted oscillations observed in longer tests (>2h), Stage 3 was introduced to enable the stable and consistent replication of activities at a physiological test rate. Despite higher RMSEs the axial error was 85.5 ± 24.27 N (equivalent to ~ 0.16 MPa), with shear RMSEs similar to other testing systems conducting pure moment tests at slower rates. The LIKE protocol enables the replication of physiological loads, providing opportunities for enhanced investigations of IVD mechanobiology, and the pre-clinical evaluation of IVD devices and therapies.

1. Introduction

Back pain is the global leading cause of years lived with disability (Buchbinder et al., 2018), incurring significant direct treatment costs, and indirect costs due to work absence and losses in productivity (Fatoye et al., 2023). Degeneration of the intervertebral disc (IVD) is often linked to low back pain, often necessitating surgical interventions such as fusion surgery or total disc replacement (TDR) when conservative therapies fail. However, the efficacy of these treatments is highly debated, with varying outcomes in pain improvement, return to work, and reoperation rates (Nguyen et al., 2011; Perfetti et al., 2021; Sköld et al., 2013) emphasising the need for better solutions to alleviate pain and restore function.

Understanding the degenerative mechanisms in the spine is crucial for improving treatment outcomes and developing preventive and rehabilitative interventions. Advances in pre-clinical testing methods can enhance treatment assessment, especially when surgical options become necessary. Prior recommendations for spinal testing methods have called for standardisation while improving physiological relevance, aiming to reduce time and cost in device development before in-vivo studies (Costi et al., 2021; Holsgrove et al., 2015; Wilke et al., 1998).

Previous spinal testing protocols have generally been based on stiffness matrix, flexibility matrix, or pure moment tests, and these are

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https://doi.org/10.1016/j.jbiomech.2023.111919
Accepted 31 December 2023
Available online 4 January 2024

Please cite this article as: D. Lazaro-Pacheco et al., *Journal of Biomechanics* , https://doi.org/10.1016/j.jbiomech.2023.111919

often limited to test rates (0.1–0.3 Hz) lower than those encountered in-vivo, along with simple sine or triangle waveforms (Costi et al., 2021; Holsgrove et al., 2015). While these tests help understand the six-axis mechanical behaviour of the spine, and the stiffness differences between slower load rates (0.1–0.3 Hz) and physiological rates (around 1–2 Hz) are relatively minor, with previous six- tests showing a 4–9 % increase in translational stiffness and a 7–17 % increase in rotational stiffness when the test rate increased from 0.1 Hz to 1 Hz (Costi et al., 2008). However, these reduced test rates, and simple waveforms limit the ability to assess how the microstructure may be affected, how devices may respond, or how cells may respond to complex physiological loads. Similarly, simplified test protocols, examining one primary axis at a time (e.g., flexion–extension, lateral bending, axial rotation), overlook the complex multi-axis loading experienced by the IVD during daily activities (Rohlmann et al., 2014; Rohlmann et al., 2008). These simplifications may limit our understanding the load transfer in the spine, the effect of degeneration, and the accurate assessment of spinal treatments. Initial studies to replicate complex physiological loading during daily activities have been undertaken (Holsgrove, 2019). However, these efforts employed a synthetic spinal specimen, and led to substantial tracking errors (quantified using the root mean squared error (RMSE) between the actual and desired loads) in flexion–extension and lateral bending axes due to force and moment coupling. Moreover, the testing system employed did not appropriately convert loads from the load cell datum to the centre of the superior vertebra during testing, hindering the application of intended loads to the local spinal specimen coordinate system. Controlling test systems to accommodate the non-linear tissue properties of biological tissues, including those in the spine, can be challenging, but a greater difficulty in multi-axis load control tests is managing coupling effects, where efforts to control one axis inadvertently impact others. This greatly increases the difficulty to minimise tracking errors between actual and desired loads, leading to issues with precision, and the potential for unwanted oscillations.

Therefore, this study aimed to use a custom six-axis spine simulator to develop a novel Load Informed Kinematic Evaluation (LIKE) protocol to replicate the complex six-axis loading of daily activities at a physiological test rate. It was hypothesised that by applying loads of daily activities in load control at a reduced test rate, the kinematics could be measured, and then used to complete subsequent tests in kinematic control at physiological test rates whilst keeping load errors within an acceptable margin. By switching from load to kinematic control, the challenge of completing tests in six-axis load control would be avoided, and the risk of unwanted oscillations due to coupled loads would be mitigated, which would be particularly valuable for multi-day, whole organ culture tests.

2. Methods

The development of the LIKE protocol involved the combination of three datasets:

- The Harmonised European Time Use Survey (HETUS) was used to develop a daily activity profile based on a UK population aged 24–44 years as reported in 2010 (European Commission, 2010)
- A limited number ($n = 20$) of daily activities were selected from the Orthoload database (Bergmann, 2008) to represent the activities included in the daily activity profile.
- The Orthoload activities were adapted for bovine tail specimens and applied in six-axis load control to create a six-axis kinematic profile dataset that could be used for both short- and long-term tests with the ability to control for diurnal changes in disc height.

The HETUS data was used to ensure that the activities, and therefore loads, included in the protocol realistically represented the activities of a relevant population. The profile was based specifically on UK adults aged 24–44 years as that age range is when back pain prevalence increases, and when degeneration is likely to initiate. A UK population was used in order to include a single nation, so as to limit cultural/social behaviour variation that may occur between national data, and with the perspective that alternative population/national activity profiles could be similarly developed in future studies. The survey data provides high-level time use data (e.g. commuting, leisure, cooking, sleeping, etc.), and therefore remains open to interpretation, but does provide a basis for the types and intensity of activities throughout the day. The allocation of time across the day was subdivided into five primary categories:

1. Personal care
2. Employment and academic pursuits
3. Household and familial responsibilities
4. Recreational activities, social engagements, group affiliations
5. Travel

These overarching primary categories collectively comprise a total of 40 distinct subcategories, as outlined within the HETUS database (Table 1 Supplementary material). The reported time spent in each subcategory was used to assign a slot in the UK baseline activity profile (UKBAP) (Fig. 1).

The Orthoload database (Bergmann, 2008) provides the most comprehensive in-vivo spinal loading data available. It comprises six-axis load data measured at 100 Hz using an instrumented vertebral body replacement (VBR) in five participants, and provides load data for hundreds of functional movements and activities of daily living. The Orthoload database was accessed, and 20 activities were chosen that could reasonably represent the 24-hour activity profile developed from the HETUS data (Table 1).

Due to the challenge of replicating the complex loads of the spine in six axes at a physiological test rate in-vitro, the LIKE protocol consisted of applying loads in six-axis load control at a reduced rate (~0.1 Hz), from which the kinematics were measured, filtered, and then these kinematics were used in kinematic control for subsequent tests at the physiological test rate. However, several stages were used to ensure that the resulting loads were adequately maintained in kinematic control, to ensure that the disc height reflected the diurnal changes observed in-vivo (Jiong Guo et al., 2022), and to prevent a risk of unwanted oscillations during long-term (multi-day) tests (Fig. 2).

The loads of the 20 activities selected were compiled into single test

Table 1
Selected Orthoload activities enabling physiologically relevant daily activities and loads through diverse movements, activity categories, and activity intensities.

ID	Orthoload activity description	Filename
1	Supine Position; lying relaxed	wp1_101210_1_4
2	Sitting down no support	wp1_290510_3_5
3	Brushing Teeth	wp4_110209_2_78
4	Sitting to lying supine	wp1_200110_1_29
5	Reaching for something on a table; sitting	wp2_050907_1_152
6	Reaching for something on a table; sitting	wp2_050907_1_148
7	Sitting; special activity	wp4_040909_1_29
8	Standing; lifting a weight from the ground knees straight; back bent	wp1_101210_1_101
9	Sweeping floor	wp1_200110_1_84
10	Standing; picking something up from ground; without aid	wp1_200110_1_75
11	Putting something on a cupboard in head level	wp2_050907_1_125
12	Sitting; relaxed	wp1_200110_1_151
13	Jogging; treadmill	wp1_301107_1_130
14	Standing; relaxed; breathing	wp1_101210_1_22
15	Standing; training with bands	wp4_200110_1_115
16	Sitting down with support by hands on bench	wp4_040909_1_40
17	Walking; upstairs	wp1_090707_1_151
18	Walking; several steps	wp1_101210_1_152
19	Cycling; 40 rpm	wp1_030212_2_3
20	Sitting; whole-body vibration	wp1_050607_2_18

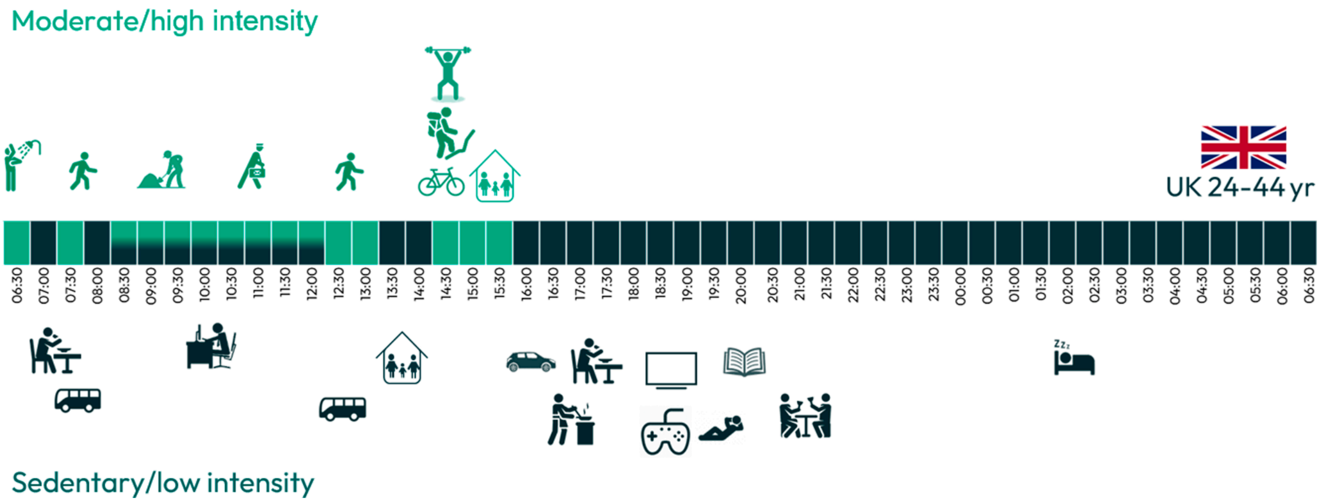

Fig. 1. UK baseline activity profile (UKBAP) based on the Harmonised European Time Use Survey (HETUS) 2010.

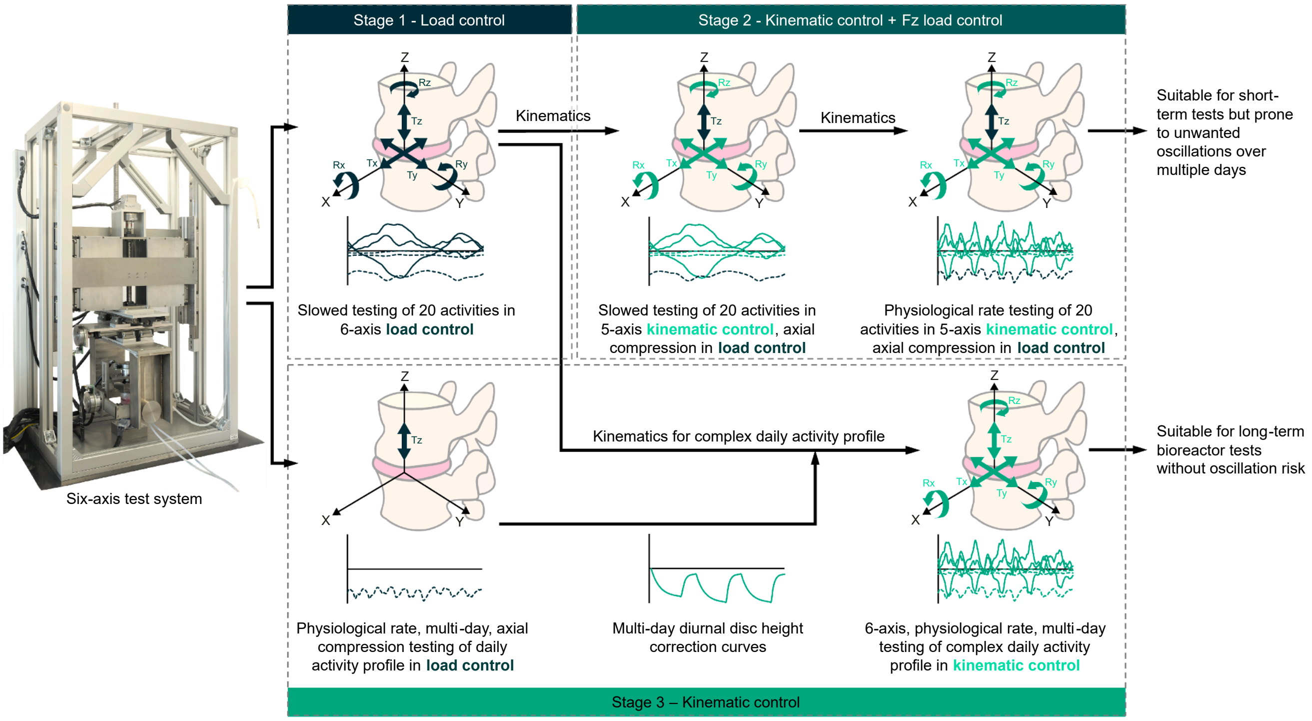

Fig. 2. A custom six-axis test system was used to complete all tests. Stage 1 used six-axis load control at a reduced test speed, stage two used kinematic control in five axes, and load control in axial compression in both slowed and physiological rate tests, and stage 3 used single-axis multi-day tests in axial compression using load control to create diurnal correction curves that were combined with the kinematics from stage 1 to provide a six-axis kinematic daily activity profile without oscillation risk for multi-day, physiological rate tests. Translational axes are denoted as Tx, Ty, and Tz for anterior-posterior shear, medial–lateral shear, and axial compression-tension respectively, and rotational axes are denoted as Rx, Ry, and Rz for lateral bending, flexion–extension, and axial rotation respectively.

profiles for stage 1 using custom Python code to create 2-second transitions between activities. This also included a linear scaling for bovine tail specimens based on cross-sectional area (520 ± 75 mm^2) with respect to a baseline human IVD cross-sectional area of 1500 mm^2 (Costi et al., 2008). The same code was used to compile the kinematic/load profiles for stage 2, and the 24-hour and multi-day profiles used in stage 3, which also included the looping of activities in order to create overall activity time periods to match HETUS data.

In stage 1 the loads of 20 Orthoload activities were applied at a reduced test rate in six-axis load control and the activities were randomised in order for each specimen. In stage 2 the kinematics of tests in stage 1 were filtered using a moving average (20 points) to create a kinematic profile for each activity. The kinematic profile was then applied in kinematic control with the exception of the axial compression axis, which was maintained in load control in order to allow disc height changes to occur as they would in-vivo. Tests were then completed in this control method at the same slowed test rate as in stage 1, and at the physiological test rate. However, whilst preliminary tests demonstrated the feasibility of this method for physiological rate testing, and the kinematics and axial force were developed into a 24-hour profile that was successfully implemented in one specimen, it was found that the coupling between axial compression, and flexion/extension and lateral bending kinematics was a potential source of unwanted oscillations, which increased the risk of compromising the results of the multi-day testing required for whole-organ IVD culture studies. Therefore, a third stage was developed for multi-day testing, which used six-axis kinematic control based on the kinematics from the activities measured in stage 1, but incorporated the diurnal disc height changes from a three-day test of the 24-hour UKBAP load profile in axial compression only, using load control. These disc height changes were used to create diurnal correction curves for the 24-hour kinematic profile, which allowed multi-day activity profiles to be completed in six-axis kinematic control and avoided any risk of unwanted oscillations.

Comparisons between the control methods of stages 1 and 2 were completed by comparing the RMSEs between the actual six-axis loads of the 20 selected activities applied to specimens and the desired loads from the scaled Orthoload data for the same activities. In stage 3 a five-day test of the 24-hour activity profile (UKBAP) was completed, but the same 20 activities were included in this profile three times a day, at times equivalent to first thing after getting up, mid-way through the day, and just prior to going to bed, and the RMSE between actual loads and the scaled Orthoload data calculated for these tests. Additional qualitative comparisons were made with respect to trends in the loads/kinematics between test stages, and in relation to the broader data available in the literature. The acquisition of load and position data for the 20 activities was completed at 100 Hz in all tests. In order to create the diurnal correction curves from the three-day axial compression testing in stage 3, load and position data was acquired continuously at 0.1 Hz during this test.

Bovine tail specimens (Cx1-Cx2 level) were used for all testing. Whole bovine tails were acquired, with the skin removed and frozen on the acquisition day. The tails were thawed overnight prior to testing, and facets and processes were removed using an oscillating saw. An alignment jig was used with the oscillating saw to cut the superior and

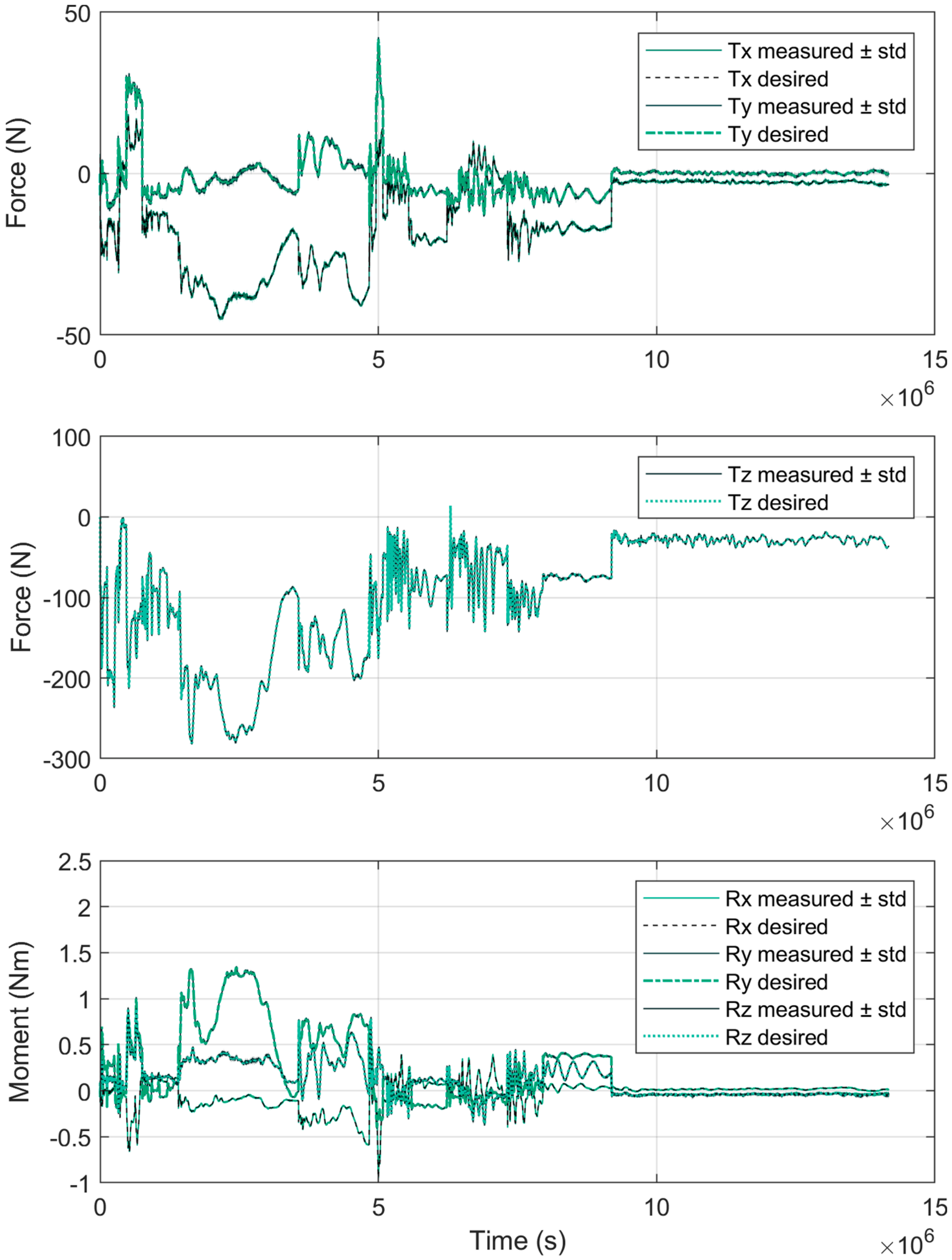

Fig. 3. Typical results of one specimen showing that the desired and actual loads closely matched in shear forces (top), axial compression (middle), and moments (bottom) for 20 daily activities using six-axis load control at a reduced test speed.

inferior vertebral bodies in the axial plane to leave approximately 10 mm of vertebral body on either side of the IVD. Specimens were then fixed into a biochamber, which was then mounted onto a custom six-axis test system. During testing the biochamber was maintained at 37 °C via heating coils that were wrapped around the base of the chamber.

In stage 1, six specimens were tested, and the biochamber was filled with phosphate buffered saline (PBS). One specimen was discounted at stage 1 due to irregular and inconsistent mechanical behaviour compared to the other specimens. This left five specimens that were taken through to stage 2 both at the slowed test rate, and at the physiological test rate. In stage 3, a single specimen was used for the axial compression testing over three days to create the diurnal correction curve, and another single specimen was used to complete the validation of the LIKE method over a 5 day test period. Both stage 3 specimens were prepared within 3 h of slaughter and tested using the Prime Growth isolation and culture media system (Grant et al., 2016) in order to prevent blood clotting from compromising fluid flow through the vertebra and IVD endplates, and to minimise the degradation of the specimen over the multi-day test period.

3. Results

To accurately evaluate the loads applied using the kinematics acquired in stage 1 the measured loads were detrended for comparison. The six-axis load control method demonstrated that the system was capable of closely replicating the desired loads at the reduced test speed (Fig. 3), and RMSE was maintained within twice the load cell noise floor in all axes (anterior-posterior shear (Tx):0.40 N; medial–lateral shear (Ty): 0.36 N; axial compression (Tz): 2.01 N; lateral bending (Rx): 0.09 Nm; flexion–extension (Ry): 0.09 Nm; axial rotation (Rz): 0.02Nm) (Table 2 and Table 2 Supplementary material).

The replication of loads using a combination of kinematic control in five axis and load control in Tz during stage 2 did increase the RMSE compared to six-axis load control (Table 2). However, at the reduced speed, the RMSE in Rx, Ry, Rz, and Tz were still maintained within two-times the noise floor of the load cell, and though shear forces (Tx and Ty) were slightly above this value in some activities (maximum 1.40 ± 1.46 N and 1.32 ± 0.77 N for Tx, and Ty respectively) (Table 2 Supplementary material), the mean across all activities was maintained within twice the load cell noise floor (Table 2). An increase in RMSE occurred when reproducing the activities with the same approach at the physiological rate, however, the errors were still relatively low considering the large magnitude and test rate variability across the different activities (Table 2 Supplementary material). The increase in RMSE when moving from the testing at a reduced speed to the physiological test rate was due to an increase in small unwanted oscillations in the Tz axis due to the coupling between bending (flexion/extension and lateral bending) and axial compression, and the increased challenge that presented in maintaining the desired Tz load at the physiological rate. The stage 3 test phase was designed to overcome this issue of unwanted oscillations, and the risk of control errors occurring during long tests (>2h), by operating in six-axis kinematic control with the addition of diurnal correction curves. The diurnal behaviour of a specimen was measured over the single-axis (Tz) load control replication of the UKBAP activity profile at the physiological test rate over the course of three days. Height loss and recovery was confirmed during this test. A height fit curve was estimated and applied to the Tz kinematic profile of the UKBAP activity created with the kinematics obtained during stage 1 (Fig. 4).

The 24 h activity profile with diurnal correction (Fig. 4) was replicated using six-axis kinematic control. All activities were successfully replicated with no noticeable oscillation during the whole test duration. However, operating in six-axis kinematic control did lead to substantially larger RMSE than in stages 1 and 2, particularly in Tz (Table 2). However, the mechanical tests of the 20 activities, which were completed three times a day showed that the loads were consistent over the five-day test period (Fig. 5), suggesting that the diurnal correction curve was successful in accounting for the IVD height changes during the 24 h activity profile without using load control.

4. Discussion

The LIKE protocol provides a novel method to replicate and stably control dynamic, complex loads representative of activities of daily living at physiological test rates. In stage 1, where load control was used to replicate the activities at a reduced speed, all activities had an RMSE within two times the load cell noise floor, which confirms the accurate replication of the activities and suggest that the kinematics recorded at this stage are adequate for the replication in subsequent stages of the LIKE protocol.

The adoption of kinematic control in 5 axes and the load control of Tz in stage 2 of the testing sequence likewise demonstrated that the RMSE was generally within two times the load cell noise floor at the reduced test rate, and above it but still relatively low during the physiological rate tests. The RMSE during the physiological rate tests in stage 2 were in fact comparable to the errors previously reported during pure moment tests at 0.01–0.3 Hz (Holsgrove et al., 2018; Lawless et al., 2014), which emphasises the value of the LIKE protocol for the application of more physiologically relevant activity profiles that involve a combination of loads in all six-axis. However, the use of this test method at the physiological test rate for long tests (>2h) led to a discernible escalation in oscillation levels, which accumulated as time advanced. Therefore, this approach is recommended for short tests (≤1h), such as biomechanical evaluations. However, for longer tests, particularly multi-day assessments such as whole organ IVD culture tests; it is advisable to use the six-axis kinematic control adopted in stage 3 of this study (Fig. 2). The diurnal correction curves successfully mimicked the natural disc behaviour, and their suitability for implementing a multi-day activity profiles using kinematic control was confirmed by maintaining consistent loads during the 20 activity tests completed at the same time each day across all five days (Fig. 5). The distinct bovine IVD geometry and morphology makes it a valuable choice for organ culture and IVD mechanical studies. Yet, inter-specimen variability, including stiffness,

Table 2

Mean ± standard deviation RMS load tracking errors for stage 1 (six-axis load control at a reduced test speed), stage 2 (five-axis kinematic control with axial compression in load control) at reduced speed and at the physiological test rate, and stage 3 using the LIKE protocol (six-axis kinematic control at the physiological test rate) for a five day test using the 24 h daily activity profile with diurnal correction. Results for stage 1 are for six specimens, stage 2 are for five specimens (one specimen was discounted after stage 1), and results for stage 3 are for the three tests of the 20 activities completed each day over the course of the five day test period in a single specimen.

Axis	Control method			
	Load control (reduced speed)	Kinematic control (reduced speed)	Kinematic control (physiological rate)	LIKE protocol
Tx (N)	0.55 ± 0.12	0.80 ± 0.30	3.45 ± 1.81	9.00 ± 7.14
Ty (N)	0.53 ± 0.09	0.77 ± 0.29	3.82 ± 1.99	9.88 ± 5.23
Tz (N)	1.62 ± 0.48	1.79 ± 0.50	11.32 ± 8.69	85.50 ± 24.27
Rx (Nm)	0.01 ± 0.004	0.02 ± 0.01	0.13 ± 0.07	0.55 ± 0.28
Ry (Nm)	0.01 ± 0.003	0.02 ± 0.01	0.16 ± 0.115	0.54 ± 0.27
Rz (Nm)	0.01 ± 0.003	0.02 ± 0.01	0.07 ± 0.042	0.15 ± 0.04

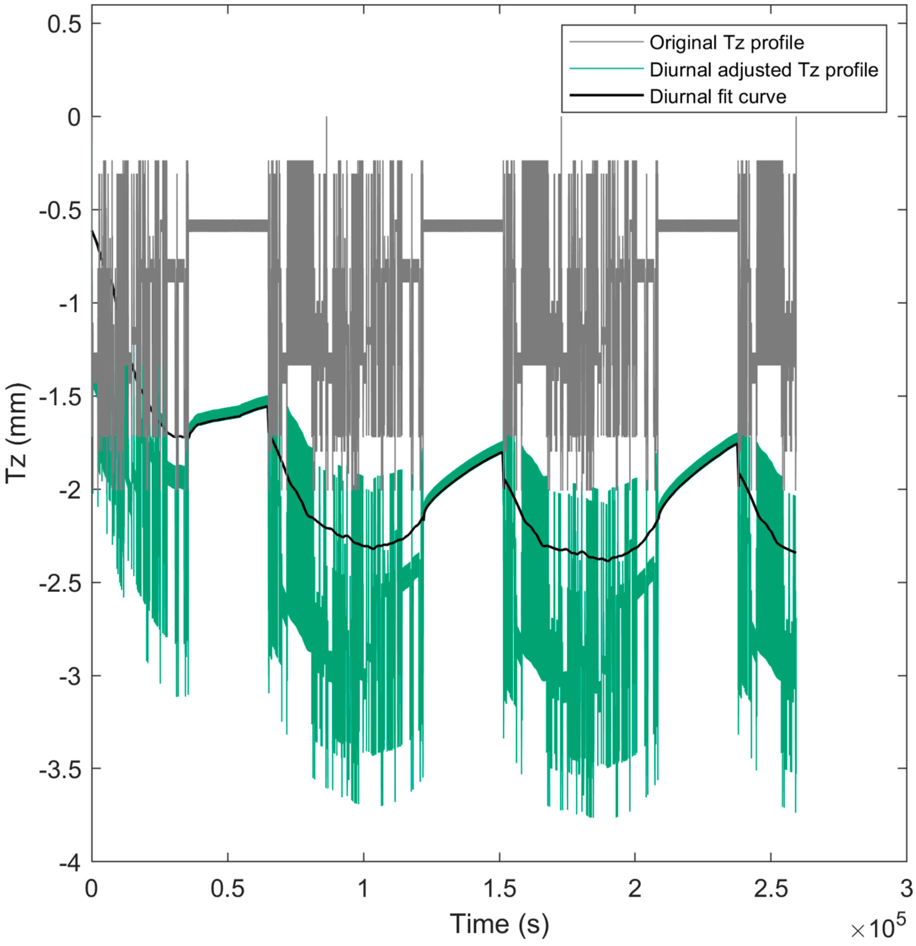

Fig. 4. Baseline Tz profile before and after the application of diurnal height correction to simulate the natural changes in IVD height caused by periods of activity and recovery over a multi-day period.

laxity, and range of motion, should be acknowledged. This variability may result in noticeable load differences when using this methodology with the averaged kinematics. Kinematic data was acquired and averaged from a cohort of five specimens sharing comparable dimensions. However, any disparities in cross-sectional area in subsequent experimental trials could influence the magnitudes of applied loads.

The replication of activity kinematics at the physiological test rate over a five day period in stage 3 of the testing resulted in an elevation of RMSE compared to the earlier stages (Table 2), and this was most notable in axial compression where the mean RMSE across all activities over the five day test period was 85.50 N. However, RMSEs of over 50 N in axial compression have been reported during pure moment flexion/extension tests at 0.1 Hz using a synthetic spinal specimen (Holsgrove et al., 2018), which presents considerably less challenging test conditions, and therefore, the errors of the present study may still provide leading capabilities in terms of replicating the complex loads of the spine during physiological activities. Furthermore, the axial load error remained equivalent to approximately 0.16 MPa, which may be within an acceptable error when considering the large range of both sedentary and higher intensity activities that are completed during normal daily activities, and that are included as part of the 24 h activity profile of the present study. Based on the intradiscal pressure range during daily activities (0.09–2.8 MPa) measured in vivo (Sato et al., 1999; Takahashi et al., 2006; Wilke et al., 2001), the error of ∼ 0.16 MPa equates to approximately 6 % of the typical pressures encountered. Similarly, the RMSE in the shear axes fall within the range of errors associated with passive XY platform and hexapod systems when completing pure moment tests at slower test rates of 0.1 Hz (Holsgrove et al., 2018). An alternative six-axis test system has been developed with a focus on operating in kinematic control at higher test speeds (Wilke et al., 2016), but this was developed specifically to provoke injury to IVD specimens, and not replicate physiological movements or loads. Notably, the advantage of the LIKE protocol lies in the capability to exert complex loads across all six axes, a departure from the limitation of pure moments. Despite the RMSEs being substantially higher when completed in six-axis kinematic control, the protocol nevertheless facilitates a groundbreaking opportunity to replicate a range of activities of daily living, which include both sedentary, and higher intensity activities at physiological rates, and the pipeline for the development of 24 h activity profiles from these activities, thereby enabling prolonged physiological testing regimes for the first time.

4.1. Limitations

Orthoload data provides six-axis load data of a vertebral body replacement, which is combined with posterior fixation. Therefore, it may underestimate IVD loading due to the load sharing between the VBR and posterior fixation. Additionally, the participants that contribute to the dataset are by the nature of having a vertebral body replacement, not healthy subjects, as the VBR results in fusion at two lumbar levels, and this may affect movement during the activities completion, which may result in different loads to a healthy population. Furthermore, the participants were aged 62–71 years at the time of VBR implantation, which may mean that the movements and loads during functional movements and daily activities varies considerably from a younger population. Limited six-axis spinal loading data is available

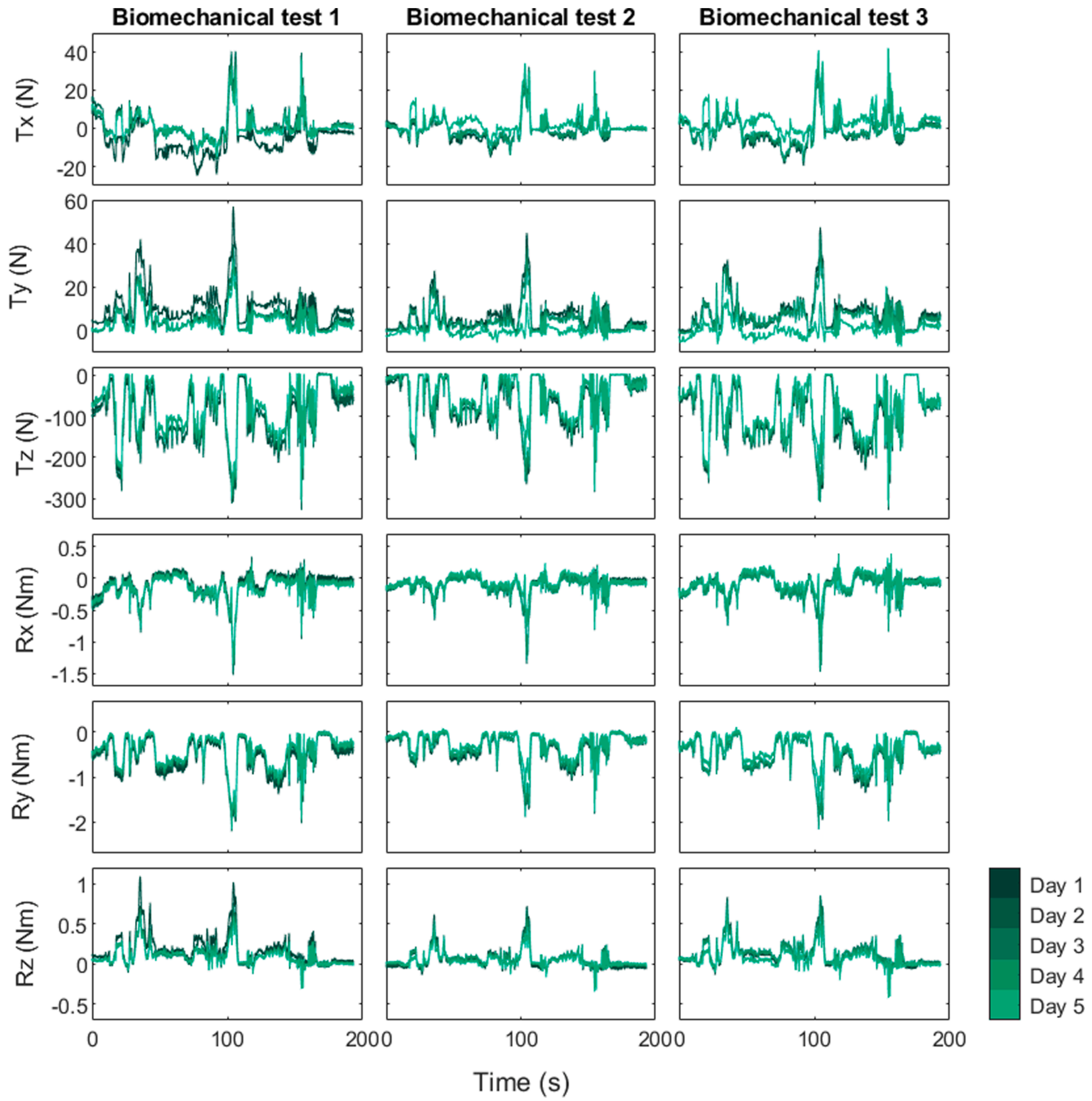

Fig. 5. Similar loads were measured during the 20 activity test that was completed throughout five days of testing at three different timepoints equivalent to just after getting up in the morning (test 1), during the middle of the day (test 2), and just prior to going to bed (test 3).

from other sources. The development of musculoskeletal models to estimate these loads in healthy populations and those with spinal issues is an exciting area of research currently pursued by the spinal community. However, data remains scarce, and validating these models remains a significant challenge.

While the daily activities used in the present study will subject discs to the complex loads experienced in-vivo, standard biomechanical tests of more functional movements such as flexion–extension, lateral bending, and axial rotation would provide a way to measure specimen stiffness. This is valuable for understanding changes over time in a single specimen tested over multiple days (e.g., cell culture systems) or evaluating devices in intact/degenerate/treated states. It can also be useful for comparing groups with different daily activity profiles. Therefore, integrating these biomechanical tests into the 24-hour activity profiles would offer clearer biomechanical outcome measures during testing.

5. Conclusions

The LIKE protocol presents a valuable approach with which to integrate complex physiological loading into in-vitro six-axis test systems over both short and long-term test periods, which has not previously been possible. The adoption of the protocol will facilitate ground-breaking investigations into disc nutrition and cell viability, degenerative mechanisms, and regenerative therapies under intricate loading conditions, and provides a way to explore the impact of different activities and lifestyles on IVD health.

CRediT authorship contribution statement

D. Lazaro-Pacheco: Conceptualization, Data curation, Writing – original draft, Writing – review & editing, Visualization, Investigation, Validation, Formal analysis, Methodology, Project administration and Software. **I. Ebisch:** Writing – review & editing, Investigation, Validation, Methodology. **T.P. Holsgrove:** Conceptualization, Funding acquisition, Writing – original draft, Writing – review & editing, Visualization, Investigation, Methodology, Supervision, Resources, Project administration, Software.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to acknowledge the EPSRC training grant (EP/T518049/1 #2606307) and the EPSRC research grant (EP/S031669/1), which supported the completion of this research. The authors thank Tom Russell for his role in creating the Python code that streamlined the processing of our activity data in this research.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2023.111919.

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