A Theoretical Framework for Relating Natural Movement to Length and Quality of Life in Human and Non-human Animals

Iain Hunter[1]

[1]Division of Neuroscience, Faculty of Biology, Medicine and Health, Manchester Academic Health Science Centre, School of Biological Sciences, University of Manchester, Manchester, United Kingdom.

Corresponding author: Iain.hunter-2@manchester.ac.uk

1 Abstract

Natural movement is clearly related to health, however, it is also highly complex and difficult to measure. Most attempts to measure it focus on functional movements in humans, and while this a valid and popular approach, assays focussed on particular movements cannot capture the range of natural movement that occurs outside them. It is also difficult to use current techniques to compare movement across different animal species. This type of interspecies comparison may be useful for identifying conserved computational principles of movement that guide human and veterinary medicine, plus several other fields of research. It is therefore important that research develops a system for quantifying movement in freely moving animals in natural environments and relating it to length and quality of life. The present text proposes a theoretical framework for doing so, within which movement is defined as movement ability (MA). MA is comprised of three major variables – Movement Quality, Movement Complexity, and Movement Quantity – that may be used to capture what are perhaps the most important components of movement as it relates to length and quality of life. The framework requires validation, however, it represents a novel and potentially important paradigm for considering movement, which may influence how present and future work is conducted.

Keywords: Behaviour, movement, locomotion, model, framework, comparative biology.

2 Introduction

Movement is fundamental to life, and it can take many forms. This work is concerned with large-scale, skeletal-level movement, and its measurement to support length and quality of life (LQOL). This type of movement is inherent in changes in joint angle, such as shoulder flexion, which contributes to a wide range of important behaviours (Gill et al., 2020). This includes reaching, which supports feeding in many animals (Whishaw et al., 2017).

A body of research has been dedicated to investigating large-scale movement and how it may support length and/ or quality of life in humans (Király and Gondos, 2014, Heinrich et al., 2015, Cholewa et al., 2014). This work often constrains movement to simplify or facilitate understanding of it. For example, there have been many instances where assessment is particular to the sort of reaching described

above (Wagner et al., 2007, Paolucci et al., 2021) or another, 'functional' movement in isolation of further movement complexity (Wagner et al., 2014, Slaughter et al., 2015, Dogu et al., 2013). Experiments that measure non-human animal movement usually take a similar, or even more abstracted approach that supports conservation (Katzner and Arlettaz, 2020). Such work is important, however, it cannot capture nor reflect much of what most natural movement represents: a highly complex, dynamic, and often whole body output that is a probabilistic function of an animal's physiology and environment (Goossens et al., 2020, Latash and Anson, 1996). The present text describes a novel theoretical framework within which it may be possible to capture some of the complexity and dynamism of natural movement and relates it to LQOL, in a way that is not possible using traditional protocols that dissect it.

The framework presented below has the potential to form the basis of a model. In addition to quantifying movement and relating it to LQOL, it represents a single system that may be used to compare natural movement both within and between species of animal (intraspecies, e.g., human to human or interspecies, e.g., human to canid, respectively). This type of comparison is important; it may facilitate the identification of general computational principles of movement conserved across animals, which could form the principal components of locomotion that should be addressed first when treating movement disorder. These principles may also be used to design more accurate movement in robots (Kashiri et al., 2018), or to describe how sensory information is processed to provide appropriate motor action selection, which could inform control theory (Zarandi and Mosadegh, 2016). Finally, interspecies comparison of natural movement may support veterinary and human medicine, conservation (Wright et al., 2020), and understanding predator-prey dynamics (Keim et al., 2021).

The framework is written to express a human or non-human animal's natural movement and the extent to which it supports length and quality of life, as Movement Ability (MA). MA has been defined as a function of three variables: Movement Quality (M_{qual}), Movement Complexity (M_{comp}) and Movement Quantity (M_{quant}). Each relates to different aspects of natural movement and is derived from several more, which are described conceptually and mathematically, in the Framework section. They are also explored in greater depth in the Discussion.

The idealised application of MA would be to calculate it from video of freely moving human or non-human animals, captured over a significant period (24h – 1w) of time in a natural environment, using a tool such as DeepLabCut (Mathis et al., 2018). It could then be analysed and applied in any one of the ways or fields described above, to relate movement to LQOL. The rationale and limitations for using this approach, and of scoring MA based on each variable, are explored in the Discussion.

In summary, the present text proposes a system for scoring Movement Ability (MA). It is hoped that researchers, clinicians (e.g. human and veterinary physiotherapists) and movement practitioners will be able to use it, or parts of it, as a means to test natural movement and relate it to LQOL in human and non-human animals.

3 Framework

3.1 Movement Ability

It is proposed that a human or non-human animal's movement ability is measured as Movement Ability (MA):

$$MA \triangleq M_{qual} \times M_{comp} \times M_{quant}$$

Where:

- M_{qual} = Movement Quality
- M_{comp} = Movement Complexity
- M_{quant} = Movement Quantity

Exemplar calculations of these variables are given at the end of each of the relevant sections below. Note that while these examples are based on humans (MA_{human} (healthy) or $MA_{humanMD}$ (movement disorder)) or mice (MA_{mouse} (healthy) or $MA_{mouseMD}$ (movement disorder)), the calculations are the same regardless of species, and may be applied to any human or non-human animal.

3.2 Movement Quality

Movement Quality (M_{qual}) is designed to score a human or non-human animal's movement to reflect the absence or presence, and probability of future development of movement dysfunction. High M_{Qual} therefore suggests absence and low probability of future dysfunction, while low M_{Qual} represents the opposite (functional disadvantage). It is expressed as:

$$M_{qual} \triangleq (M_{acc} + M_{co}) \times M_{pain}$$

Where:

M_{acc} = movement accuracy scored from 0-1. Based on decimal of percentage of recording time (rt), in which joint angle(s) of all major joints exist within their safe ranges (1 = 100%, 0.5 = 50% etc.), while changing angle to an extent and with a rate and directional variability consistent with normal motor control.

$$M_{acc} \triangleq 1 \times (\%rtj_{\emptyset_{safe}} + \Delta j_{\emptyset_{NMC}} + \Delta j_{\emptyset} r_{NMC} + j_{\emptyset_{var_{NMC}}})$$

Joint (j) is defined as the centre of the fulcrum responsible for articulation of a body part, which contributes to movement or locomotion of human or non-human animal. Joint angle ($j_{\emptyset}$) is measured as three-dimensional angle ($\emptyset$) formed between positions of j and most distal component of body part in x, y and z axes of space (x, y and z below), where it either forms another joint (e.g. hip to knee at femur) or terminates to complete a particular part of the body plan (e.g. atlanto-occipital joint to nose):

$$j_{\emptyset} = cos\,(x + y + z)/(\sqrt{(x + y + z)})$$

Safe joint angle $\left(j_{\emptyset_{safe}}\right)$ is defined as $j_{\emptyset}$ which is equal to or less that the anatomically determined range appropriate to a given joint (j_{anat}), e.g., $x_{0^\circ} - x_{180^\circ}$ for a hinge joint:

$$j_{\emptyset_{safe}} \triangleq j_{\emptyset} \leq j_{anat}$$

Extent of change in joint angle is measured as the difference in three-dimensional joint angle ($\Delta j_{\emptyset}$, a vector) of a given joint, which occurs between two points in recording time:

$$\Delta j_{\emptyset} = \mathrm{arc}_{cos}[(x_a \times x_b + y_a \times y_b + z_a \times z_b)/(\sqrt{(x_a 2 + y_a 2 + z_a 2)} \times \sqrt{(x_b + y_b 2 + z_b 2)})]$$

Extent of change in joint angle consistent with normal control of movement ($\Delta j_{\emptyset_{NCM}}$) is defined as that which occurs within ± 2 standard deviations (2σ) of the mean unidirectional displacement of that joint in a sample of healthy human or non-human animals of the same species. It is therefore defined as:

$$\Delta j_{\emptyset_{NCM}} \triangleq \overline{\Delta J_{\emptyset}} \leq \overline{\Delta J_{\emptyset}}^{2\sigma}$$

Rate of change in joint angle is measured as the velocity with which $j_{\emptyset}$ changes ($\Delta j_{\emptyset} r$, t = time).

$$\Delta j_{\emptyset} r = \mathrm{arc}_{cos}[(x_a \times x_b + y_a \times y_b + z_a \times z_b)/(\sqrt{(x_a 2 + y_a 2 + z_a 2)} \times \sqrt{(x_b + y_b 2 + z_b 2)})]/\,t$$

Rate of change in joint angle consistent with normal control of movement ($\Delta j_{\emptyset} r_{NCM}$ is defined as that which occurs within ± 2 standard deviations (2σ) of the mean rate of change recorded in a sample of healthy human or non-human animals of the same species:

$$\Delta j_{\emptyset} r_{NCM} \triangleq \Delta j_{\emptyset} r \leq \Delta j_{\emptyset} r^{2\sigma}$$

Directional variability is expressed as variance of joint angle ($j_{\emptyset_{var}}$) observed during recording time. Thus, directional variability consistent with normal control of movement ($j_{\emptyset_{var_{NCM}}}$, is the variance of $j_{\emptyset}$ that is less than or equal to the variance recorded in a sample of healthy human or non-human animals of the same species (σ^2):

$$j_{\emptyset_{var_{NCM}}} \triangleq j_{\emptyset_{var}} \leq j_{\emptyset_{var}} \sigma^2$$

M_{co} = movement coordination is scored from 0-1, based on decimal expression of percentage of recording time (rt) in which the relative positions of two or more joints are consistent with normally coordinated movement (1 = 100%, 0.5 = 50% etc.)

$$M_{co} \triangleq 1 \times (\%rt\Delta j_{\emptyset} r_{NMC})$$

The relative positions of two joints ($j_{pos_{a,b}}$, where a and b define different joints) is expressed in a similar way to $\Delta j_{\emptyset}$. It is:

$$j_{pos_{a,b}} = arc_{cos}$$

When relating the positions of more than two (three) joints ($j_{pos_{(a,b,c)}}$, the shared angle is expressed using a scalar product form formula to find the Cartesian equation of the plane formed by those joints:

$$j_{pos_{(a,b,c)}} \triangleq \vec{n} \cdot \vec{r} = \vec{n} \cdot \vec{x}$$

Where $\vec{n}$ is any vector normal to the plane and $\vec{r}$ is a generic vector in 3-dimensional space (e.g. q, r, s). Relative position of two or more joints consistent with normally coordinated movement ($j_{pos_{a,b\ldots NCM}}$) describes that which occurs within ± 2 standard deviations ($2s$) of the mean rate of change recorded in a sample of healthy human or non-human animals of the same species

$$j_{pos_{a,b\ldots NCM}} \triangleq j_{pos_{a,b\ldots}} \leq j_{pos_{a,b\ldots}}{}^{2s}$$

M_{pain} = likelihood of pain present in movement, based on avoidance scored from 0-1. Specifically, it is quantified as the inverse decimal percentage of avoidance of a behaviour correlated with a human or non-human animal's survival $\left(M_{pain(x)}\right)$, versus its mean occurrence in a healthy sample:

$$M_{pain(x)} \triangleq 1 - (x_{\%avoid})$$

Behaviour(s) correlated with a human or non-human animal's survival are defined by its species-specific ethogram. All these behaviours are scored for M_{pain}, however, only the lowest scoring (i.e. largest avoidance, given as x below) is entered into the equation for M_{qual}. M_{pain} may therefore be expressed as:

$$M_{pain} = M_{pain(x)}$$

In summary, assuming a recording time of 24h and arbitrary units, M_{qual} may be scored as:

- $(0.9 + 0.9) \times 1 = 1.8$, for MA_{human} that moves with a high degree of accuracy and coordination, without avoiding behaviour correlated with survival.
- $(0.51 + 0.6) \times 0.8 = 0.96$, for $MA_{humanMD}$ that moves with a relatively low degree of accuracy and coordination, while occasionally avoiding behaviour correlated with survival.
- $(0.96 + 0.94) \times 1 = 1.9$, for MA_{mouse} that moves with a slightly greater degree of accuracy and coordination than the MA_{human}, without avoiding behaviour correlated with survival.
- $(0.48 + 0.66) \times 0.7 = 0.86$, for $MA_{mouseMD}$ that moves with a low degree of accuracy and coordination that is similar to $MA_{humanMD}$, while avoiding behaviour correlated with survival more regularly.

3.3 Movement Complexity

Movement Complexity (M_{comp}) expresses the complexity inherent in human or non-human animal's movement. High M_{comp} represents movement that is varied and difficult to predict, given the series of (other) movements performed prior to it. Low M_{comp} reflects more repetitive and predictable movement. It is defined as:

$$M_{comp} \triangleq EMC_x$$

Where:

EMC= Effective Measure Complexity (Grassberger, 1986), and x is a sequence of alignments (a. Alignment (a is the momentary position of a human or non-human animal during movement, measured as the orientation of its rostrocaudal axis in three-dimensional space, plus the orientation of head and limbs (where they are present) relative to the body. EMC_x, therefore, calculates the ability to accurately predict the occurrence of a particular alignment (a within x, i.e., according to the series of (other) alignments that precede it. It may be expressed as follows:

$$EMC_x = \sum_{a=1}^{\infty} a\Delta h_a$$

Where h_a is a 'new' alignment. Note that alignments are converted into symbols to be processed as a string, as is common in the field.

Thus, assuming a total recording time of 24h and arbitrary units, M_{comp} may be scored as:

- 100 for $M_{comp_{human}}$ that conducts a weekly tumbling practice, which produces a complexity score that is considerably above the human population mean.
- 38 for $M_{comp_{humanMD}}$ that changes alignment only as much as is necessary to perform basic movements to support survival.
- 135 for $M_{comp_{mouse}}$ that produces highly complex movement (e.g. climbing, inverting and compression) as part of navigating an environment which demands it.
  23 for $M_{comp_{mouseMD}}$ that cannot change alignment as its heathy counterpart can, so, like $M_{comp_{humanMD}}$, only does so as much as is necessary to support survival.

3.4 Movement Quantity

Movement Quantity (M_{quant}) reflects the amount of movement a human or non-human animal produces during recording time. Specifically, it considers the range of movement velocity, total displacement and change in alignment observed. Thus, high M_{quant} may indicate that a human or non-human animal has the capacity to move with a high maximum velocity, over long distances. It is expressed as follows:

$$M_{Quant} \triangleq v_{range} \times d$$

Where:

v_{range} is range of movement velocity, calculated from are highest and lowest non-idle centre of mass velocities observed during recording time:

$$v_{range} = \mathbf{v}_{max} - \mathbf{v}_{min}$$

d is the total distance travelled by the animal's centre of mass ($c.o.m._x - c.o.m._y$) as defined by the limits of the sum ($c.o.m. = 1 \rightarrow c.o.m. \infty$):

$$d = \sum_{c.o.m.=1}^{\infty} c.o.m._x - c.o.m._y$$

Assuming recording time of 24h, M_{quant} may be scored (using m/s for v_{range} and km for d):

- $3.35 \times 12 = 42.2$, for MA_{human} that ran a marathon, and then was idle for most of the rest of the day.
- $2 \times 4 = 8$, for $MA_{humanMD}$ that only moved a relatively short distance, slowly.
- $2 \times 6 = 12$, for MA_{mouse} that was highly active, but due its size, did not move as quickly or as far as the marathon-running MA_{human}.
- $0.17 \times 2 = 0.34$, for $MA_{mouseMD}$ that like the $MA_{humanMD}$, only moved a very short distance, slowly.

3.5 Calculations of Movement Ability

Combining the exemplar calculations of M_{qual}, M_{comp} and M_{quant}, demonstrates that MA may be given as follows:

- $MA_{human} = 1.8 \times 100 \times 40.2 = 7{,}236$
- $MA_{humanMD} = 0.96 \times 38 \times 8 = 291.84$
- $MA_{mouse} = 1.9 \times 135 \times 12 = 3{,}078$
- $MA_{mouseMD} = 0.86 \times 23 \times 0.34 = 7.73$

4 Discussion

The exemplar scores for MA and each of its major variables (M_{qual}, M_{comp} and M_{quant}) demonstrate the potential utility of the framework. Specifically, the higher score for the healthy human ($7{,}236$) and lower for the movement disorder patient (291.84) shows that assuming it is validated (see below), it may be used to relate natural movement to LQOL. The examples also show that comparisons may be drawn between different animals of the same species ($3{,}078$ versus 7.73 for healthy and movement

disorder mice, respectively), and between different species ($7{,}236$ versus $3{,}078$ for a healthy human and mouse, respectively). As mentioned previously, these types of comparisons may be useful in identifying computational principles of movement. They could also inform fields concerned with medicine and veterinary medicine/ rehabilitation (Tarakad, 2020), optimising training programs designed to increase LQOL in already healthy human and non-human animals, robotics (Aguilar et al., 2016), action selection, control theory (Zarandi and Mosadegh, 2016), conservation (Wright et al., 2020) and understanding predator/ prey dynamics (Keim et al., 2021).

It is important to highlight that the potential utility of the framework is facilitated by its novel structure. As stated in the Introduction, the complexity of 'complete' natural movement makes it very difficult to manufacture a means of measuring and comparing it. Traditional approaches to measurement are, therefore, highly constrained by design. The present model affords significantly greater flexibility because it is based on "higher-order" principles that reflect commonalities of movement, which are not limited by peculiarities of individual animals or even species. These principles are defined in the primary variables of M_{qual}, M_{comp} and M_{quant}, and it is possible that they are broad enough for all parameters that describe natural movement to fall under them. This important idea – that quality, complexity and quantity are sufficient to explain differences in movement between animals - must be tested in future work. Specifically, it should ask the question: Are there any variables or components of movement which cannot reasonably fit under the headings of Movement Quality, Movement Complexity and Movement Quantity?

Next, given their novelty and importance to MA, it is important to discuss how the author arrived at and defined the three primary variables. Movement Quality (M_{qual}) was selected because of its clear importance to LQOL. 'Poor' (low quality) movement is related to injury and even death (Lohman et al., 2019). Normal and dysfunctional movement have been characterised biomechanically (Morris et al., 2001), and physiotherapy aims to treat the latter to restore the former. Similarly, popular culture encourages regular exercisers to focus on technique or 'form'. In contrast to this broad focus on movement quality, it is notoriously difficult to define and measure it. Most attempts to do so, which (arguably) include the functional movement screen (FMS), are: (1) constrained to human functional movements; (2) the centre of notable controversy regarding their effectiveness (Frost et al., 2012, Beardsley and Contreras, 2014). The parameters chosen to define M_{qual} here were, therefore, based on what seem to be sensible relationships regarding the biomechanical accuracy, overall coordination and pain experienced during movement, and how they relate to LQOL (Lu and Chang, 2012, Dunsky, 2019, Ferrell, 1995). It is, however, important to note that despite the logical nature of the links made, they are open to debate. This is particularly true in the case of pain during movement (Breivik et al., 2008), however, the framework may contribute something useful to that field. Specifically, it describes scoring pain as a percentage of avoidance of behaviours correlated with survival, which are identified in an animal's ethogram. This method, which to the author's knowledge is novel, may be used in addition to subjective measurements of pain (e.g. grimace scores (Cohen and Beths, 2020)) to improve accuracy. Future work should continue to pursue clarity in how movement quality relates to LQOL.

Movement Complexity (M_{comp}) is clearly necessary for the survival of some animals (e.g. birds catching insects, or land animals evading predators), so it must feature in a system designed to relate movement to LQOL across species. Though the role that movement complexity plays in the lives of modern humans is less obvious, it seems likely that it contributes to LQOL. The ability to produce varied movement surely provides a person with opportunity that is unavailable to patients with disorders characterised by repetitive movement (Sanger et al., 2010). Interestingly, and perhaps consistent with it having some importance, humans are inherently capable of appreciating the aesthetics of complex movement (Christensen and Calvo-Merino, 2013). It is therefore important to note that as for all of the other components of movement given here, it is very difficult to measure movement complexity. Indeed, much research is dedicated to how to define and quantify complexity generally (i.e. outwith movement); some of it inspired the definition of M_{comp} using effective measure complexity (EMC (Grassberger, 1986)). EMC provides the ability to code alignments as symbols, and then express the complexity of a sequence of alignments using them. This novel application of an established paradigm, therefore, provides utility in this framework and could also be used in other contexts. It may, for example, be valuable to compare the complexity of movement produced by Parkinson's Disease patients following different treatments, to help decide which was most effective. Finally, it is difficult to design robots to move with the level of complexity (e.g., dexterity) present in animals (Xia et al., 2022). M_{comp} may be used to test and improve it.

Given that Movement Quantity (M_{quant}) describes the total and range of velocity of the displacement of a human or non-human animal, it can be related to 'fitness'. This helps explain the importance of M_{quant} to the MA model, because arguably the best definition of fitness is that of an animal or non-human animal's ability to produce power ($work/time$ (Knudson, 2009)). Reasonable extrapolation allows research to link power with LQOL (Lee et al., 1995), so that there is precedence for measurements related to M_{quant} improving the latter. It is important that M_{quant} is used in the framework instead of power, because calculating power artificially biases larger animals; they must work harder (produce more power) to move themselves the same distance as animals with less mass. This may affect the relationship of power with LQOL, as high mass due to poor body composition reduces LQOL in most animals (Toss et al., 2012). Thus, using displacement and range of velocity in the model, as opposed to power, may provoke thought in research communities concerned with describing fitness. It may, for instance, inspire future use of displacement and range of velocity, or a mass-adjusted version of power, in future assessment of fitness.

Finally, and as alluded to above, it is important to confirm the value of the present framework by validating it. This validation would be technically challenging, if conducted according to the idealised conditions described in the Introduction – that is, by recording the behaviour of human or non-human animals in natural environments for 24h-1w and relating it to LQOL. It would require ensuring that reasonably unobstructed and continuous monitoring of behaviour, and the large amounts of data generated would have to be stored and analysed to test the model. It would also require an ability to track LQOL in animals, following those recordings. Validation may, therefore, be conducted in stages. For example, it may be useful to test M_{quant} using data recorded in wild populations of animals filmed

by drone, in relatively open terrain, in a much shorter timeframe than proposed earlier. Indeed, the environment afforded by research such as that conducted by the Isle of Rum Red Deer Project would suit this validation. Once this process is complete, a variation of it could be applied to validating the other 'primary' variables associated with MA (M_{qual} and M_{comp}). This would take some time and effort, but the potential utility of the framework suggests it is worth it. With enough time, MA could be used to make important links between natural movement and LQOL, by recording it in even the most technically challenging conditions. These include those related to tracking humans that move through cities, or non-human animals that migrate long distances in adverse weather conditions.

5 Conclusions

Movement Ability (MA) represents a novel means by which to measure 'holistic' or complete movement of human and non-human animals in their natural environments, and relate it to length and quality of life. MA is defined by three 'primary' variables: M_{qual}, M_{comp} and M_{quant}, which may be sufficient for describing parameters of natural movement. In addition to this possible sufficiency, each variable provides mathematical and conceptual description of parameters that could inspire future research regarding movement; M_{qual} suggests quality may be represented by accuracy, coordination and pain; M_{comp} that complexity could be expressed as the effective measure complexity of an alignment in a series of alignments, and M_{quant} that quantity of movement, which is related to fitness, may be expressed by displacement and range of velocity. In combination, they provide an important new paradigm that facilitates comparisons of movement between species of human and non-human animals, which are not possible using other protocols. MA, therefore, has the potential to be validated and used to identify principles of movement related to length and quality of life to inform medicine, veterinary medicine, and many other fields of research.

6 Statements and Declarations

Work on this project was supported by funding from the Wellcome Trust, awarded to Richard Baines (217099/Z/19/Z). Declarations of interest: none.

7 Acknowledgements

The author thanks Prof Richard Baines and Dr Cengiz Gunay, who provided valuable feedback on the text.

8 References

BACKSTROM, D., GRANASEN, G., DOMELLOF, M. E., LINDER, J., MO, S. J., RIKLUND, K., ZETTERBERG, H., BLENNOW, K. & FORSGREN, L. 2018. Early predictors of mortality in parkinsonism and Parkinson disease A population-based study. *Neurology,* 91**,** E2045-E2056.

CHOLEWA, J., GORZKOWSKA, A., SZEPELAWY, M., NAWROCKA, A. & CHOLEWA, J. 2014. Influence of Functional Movement Rehabilitation on Quality of Life in People with Parkinson's Disease. *Journal of Physical Therapy Science,* 26**,** 1329-1331.

DOGU, B., SIRZAI, H., YILMAZ, F., POLAT, B. & KURAN, B. 2013. Effects of isotonic and isometric hand exercises on pain, hand functions, dexterity and quality of life in women with rheumatoid arthritis. *Rheumatology International,* 33**,** 2625-2630.

GILL, T. K., SHANAHAN, E. M., TUCKER, G. R., BUCHBINDER, R. & HILL, C. L. 2020. Shoulder range of movement in the general population: age and gender stratified normative data using a community-based cohort. *BMC Musculoskeletal Disorders,* 21.

GOOSSENS, S., WYBOUW, N., VAN LEEUWEN, T. & BONTE, D. 2020. The physiology of movement. *Movement Ecology,* 8.

GRASSBERGER, P. 1986. TOWARD A QUANTITATIVE THEORY OF SELF-GENERATED COMPLEXITY. *International Journal of Theoretical Physics,* 25**,** 907-938.

HEINRICH, K. M., BECKER, C., CARLISLE, T., GILMORE, K., HAUSER, J., FRYE, J. & HARMS, C. A. 2015. High-intensity functional training improves functional movement and body composition among cancer survivors: a pilot study. *European Journal of Cancer Care,* 24**,** 812-817.

KASHIRI, N., ABATE, A., ABRAM, S. J., ALBU-SCHAFFER, A., CLARY, P. J., DALEY, M., FARAJI, S., FURNEMONT, R., GARABINI, M., GEYER, H., GRABOWSKI, A. M., HURST, J., MALZAHN, J., MATHIJSSEN, G., REMY, D., ROOZING, W., SHAHBAZI, M., SIMHA, S. N., SONG, J. B., SMIT-ANSEEUW, N., STRAMIGIOLI, S., VANDERBORGHT, B., YESILEVSKIY, Y. & TSAGARAKIS, N. 2018. An Overview on Principles for Energy Efficient Robot Locomotion. *Frontiers in Robotics and Ai,* 5.

KEIM, J. L., DEWITT, P. D., WILSON, S. F., FITZPATRICK, J. J., JENNI, N. S. & LELE, S. R. 2021. Managing animal movement conserves predator–prey dynamics. *Frontiers in Ecology and the Environment,* 19**,** 379-385.

KIRÁLY, E. & GONDOS, T. 2014. The effect of functional movement ability on the quality of life after total hip replacement. *Journal of Clinical Nursing,* 23**,** 124-131.

LATASH, M. L. & ANSON, J. G. 1996. What are “normal movements” in atypical populations? *Behavioral and Brain Sciences,* 19**,** 55-68.

MATHIS, A., MAMIDANNA, P., CURY, K. M., ABE, T., MURTHY, V. N., MATHIS, M. W. & BETHGE, M. 2018. DeepLabCut: markerless pose estimation of user-defined body parts with deep learning. *Nature Neuroscience,* 21**,** 1281-1289.

MAZZONI, P., HRISTOVA, A. & KRAKAUER, J. W. 2007. Why don't we move faster? Parkinson's disease, movement vigor, and implicit motivation. *Journal of Neuroscience,* 27**,** 7105-7116.

PAOLUCCI, T., BERNETTI, A., BAI, A. V., CAPOBIANCO, S. V., BONIFACINO, A., MAGGI, G., IPPOLITONI, G., TINELLI, L., SANTILLI, V., AGOSTINI, F., PAOLONI, M. & MANGONE, M. 2021. The recovery of reaching movement in breast cancer survivors: two different rehabilitative protocols in comparison. *European Journal of Physical and Rehabilitation Medicine,* 57**,** 137-147.

PARK, K., ROEMMICH, R. T., ELROD, J. M., HASS, C. J. & HSIAO-WECKSLER, E. T. 2016. Effects of aging and Parkinson's disease on joint coupling, symmetry, complexity and variability of lower limb movements during gait. *Clinical Biomechanics,* 33**,** 92-97.

POWELL, D. W., MUTHUMANI, A. & XIA, R. P. 2014. Parkinson's Disease is Associated With Greater Regularity of Repetitive Voluntary Movements. *Motor Control,* 18**,** 263-277.

ROEMMICH, R. T., FIELD, A. M., ELROD, J. M., STEGEMOLLER, E. L., OKUN, M. S. & HASS, C. J. 2013. Interlimb coordination is impaired during walking in persons with Parkinson's disease. *Clinical Biomechanics,* 28**,** 93-97.

SLAUGHTER, S. E., WAGG, A. S., JONES, C. A., SCHOPFLOCHER, D., ICKERT, C., BAMPTON, E., JANTZ, A., MILKE, D., SCHALM, C., LYCAR, C. & ESTABROOKS, C. A. 2015. Mobility of Vulnerable Elders Study: Effect of the Sit-to-Stand Activity on Mobility, Function, and Quality of Life. *Journal of the American Medical Directors Association,* 16**,** 138-143.

TARAKAD, A. 2020. Clinical Rating Scales and Quantitative Assessments of Movement Disorders. *Neurologic Clinics,* 38**,** 231-254.

WAGNER, J. M., DROMERICK, A. W., SAHRMANN, S. A. & LANG, C. E. 2007. Upper extremity muscle activation during recovery of reaching in subjects with post-stroke hemiparesis. *Clinical Neurophysiology,* 118**,** 164-176.

WAGNER, J. M., KREMER, T. R., VAN DILLEN, L. R. & NAISMITH, R. T. 2014. Plantarflexor Weakness Negatively Impacts Walking in Persons With Multiple Sclerosis More Than Plantarflexor Spasticity. *Archives of Physical Medicine and Rehabilitation,* 95**,** 1358-1365.

WHISHAW, I. Q., FARAJI, J., KUNTZ, J. R., MIRZA AGHA, B., METZ, G. A. S. & MOHAJERANI, M. H. 2017. The syntactic organization of pasta-eating and the structure of reach movements in the head-fixed mouse. *Scientific Reports,* 7.

WRIGHT, S. J., HEURICH, M., BUCHMANN, C. M., BÖCKER, R. & SCHURR, F. M. 2020. The importance of individual movement and feeding behaviour for long-distance seed dispersal by red deer: a data-driven model. *Movement Ecology,* 8.

ZARANDI, M. H. F. & MOSADEGH, H. 2016. Robotics and Control Systems. *Fuzzy Logic in Its 50th Year: New Developments, Directions and Challenges,* 341**,** 283-308.

AGUILAR, J., ZHANG, T. N., QIAN, F. F., KINGSBURY, M., MCINROE, B., MAZOUCHOVA, N., LI, C., MALADEN, R., GONG, C. H., TRAVERS, M., HATTON, R. L., CHOSET, H., UMBANHOWAR, P. B. & GOLDMAN, D. I. 2016. A review on locomotion robophysics: the study of movement at the intersection of robotics, soft matter and dynamical systems. *Reports on Progress in Physics,* 79.

BEARDSLEY, C. & CONTRERAS, B. 2014. The Functional Movement Screen: A Review. *Strength and Conditioning Journal,* 36**,** 72-80.

BREIVIK, H., BORCHGREVINK, P. C., ALLEN, S. M., ROSSELAND, L. A., ROMUNDSTAD, L., HALS, E. K. B., KVARSTEIN, G. & STUBHAUG, A. 2008. Assessment of pain. *British Journal of Anaesthesia,* 101**,** 17-24.

CHRISTENSEN, J. F. & CALVO-MERINO, B. 2013. Dance as a Subject for Empirical Aesthetics. *Psychology of Aesthetics Creativity and the Arts,* 7**,** 76-88.

COHEN, S. & BETHS, T. 2020. Grimace Scores: Tools to Support the Identification of Pain in Mammals Used in Research. *Animals,* 10.

DUNSKY, A. 2019. The Effect of Balance and Coordination Exercises on Quality of Life in Older Adults: A Mini-Review. *Frontiers in Aging Neuroscience,* 11.

FERRELL, B. R. 1995. THE IMPACT OF PAIN ON QUALITY-OF-LIFE - A DECADE OF RESEARCH. *Nursing Clinics of North America,* 30**,** 609-&.

FROST, D. M., BEACH, T. A. C., CALLAGHAN, J. P. & MCGILL, S. M. 2012. USING THE FUNCTIONAL MOVEMENT SCREEN (TM) TO EVALUATE THE EFFECTIVENESS OF TRAINING. *Journal of Strength and Conditioning Research,* 26**,** 1620-1630.

GRASSBERGER, P. 1986. TOWARD A QUANTITATIVE THEORY OF SELF-GENERATED COMPLEXITY. *International Journal of Theoretical Physics,* 25**,** 907-938.

KATZNER, T. E. & ARLETTAZ, R. 2020. Evaluating Contributions of Recent Tracking-Based Animal Movement Ecology to Conservation Management. *Frontiers in Ecology and Evolution,* 7.

KNUDSON, D. V. 2009. CORRECTING THE USE OF THE TERM "POWER" IN THE STRENGTH AND CONDITIONING LITERATURE. *Journal of Strength and Conditioning Research,* 23**,** 1902-1908.

LEE, I. M., HSIEH, C. C. & PAFFENBARGER, R. S. 1995. EXERCISE INTENSITY AND LONGEVITY IN MEN - THE HARVARD ALUMNI HEALTH STUDY. *Jama-Journal of the American Medical Association,* 273**,** 1179-1184.

LOHMAN, M. C., SONNEGA, A. J., NICKLETT, E. J., ESTENSON, L. & LEGGETT, A. N. 2019. Comparing Estimates of Fall-Related Mortality Incidence Among Older Adults in the United States. *Journals of Gerontology Series a-Biological Sciences and Medical Sciences,* 74**,** 1468-1474.

LU, T. W. & CHANG, C. F. 2012. Biomechanics of human movement and its clinical applications. *Kaohsiung Journal of Medical Sciences,* 28**,** S13-S25.

MORRIS, M. E., HUXHAM, F., MCGINLEY, J., DODD, K. & IANSEK, R. 2001. The biomechanics and motor control of gait in Parkinson disease. *Clinical Biomechanics,* 16**,** 459-470.

SANGER, T. D., CHEN, D. F., FEHLINGS, D. L., HALLETT, M., LANG, A. E., MINK, J. W., SINGER, H. S., ALTER, K., BEN-PAZI, H., BUTLER, E. E., CHEN, R., COLLINS, A., DAYANIDHI, S., FORSSBERG, H., FOWLER, E., GILBERT, D. L., GORMAN, S. L., GORMLEY, M. E., JINNAH, H. A., KORNBLAU, B., KROSSCHELL, K. J., LEHMAN, R. K., MACKINNON, C., MALANGA, C. J., MESTERMAN, R., MICHAELS, M. B., PEARSON, T. S., ROSE, J., RUSSMAN, B. S., STERNAD, D., SWOBODA, K. J. & VALERO-CUEVAS, F. 2010. Definition and Classification of Hyperkinetic Movements in Childhood. *Movement Disorders,* 25**,** 1538-1549.

TOSS, F., WIKLUND, P., NORDSTROM, P. & NORDSTROM, A. 2012. Body composition and mortality risk in later life. *Age and Ageing,* 41**,** 677-681.

XIA, Z. W., DENG, Z., FANG, B., YANG, Y. Y. & SUN, F. C. 2022. A review on sensory perception for dexterous robotic manipulation. *International Journal of Advanced Robotic Systems,* 19.