INTERNATIONAL DESIGN CONFERENCE – DESIGN 2024
https://doi.org/10.1017/pds.2024.221

An AI-based prosthesis framework fostering an adaptive amputee healthcare service

Nicholas Patiniott [1,✉], Jonathan C. Borg [1], Emmanuel Francalanza [1], Joseph P. Zammit [1], Pierre Vella [1], Alfred Gatt [1] and Kristin Paetzold-Byhain [2]

[1] University of Malta, Malta, [2] Technische Universität Dresden, Germany

✉ nicholas.patiniott@um.edu.mt

Abstract

Despite technological and medical advances, amputations continue to increase. Amputees face significant challenges when acquiring and using prosthetic devices, challenges which are made worse as their emotional needs, aspirations, mobility, prosthesis requirements and problems change over time. These challenges require custom solutions for each individual amputee, a fact that current amputee centered prosthesis services tend to ignore. The work reported in this paper contributes an AI based Prosthesis Development Service Framework to cater for the current and evolving needs of amputees.

Keywords: product-service systems (PSS), health services, healthcare design, digital twin, AI for smart product service systems

1. Introduction

Despite advances made in medicine and technology, Upper Limb (*UL*) and Lower Limb (*LL*) amputations (for a variety of reasons) continue to increase (Jennifer Spector and Editor, 2020; Casciato *et al.*, 2023; Eidmann *et al.*, 2023). These amputees face significant challenges when acquiring and using prosthetic devices. These challenges are further amplified when one considers that their emotional needs, aspirations, mobility and prosthesis related problems constantly change over time (Young *et al.*, 2019), both at the macro and micro level (Figure 1), a fact that current patient centered prosthesis services tend to ignore. This is a monumental challenge since the needs differ from amputee to amputee, which in turn requires custom solutions (in terms of their prosthesis and the aftercare service) for each individual amputee.

One example of the many challenges that are faced is the considerable time that it takes for an amputee's prosthesis to be designed, standard parts to be ordered and delivered, and the personal parts to be fabricated. All these components must then be correctly assembled together to form the whole prosthesis. As the amputee uses their prosthesis, alterations and improvements will need to be made to the prosthesis due to wear and deterioration of the prosthesis, as well as the evolving needs of the amputee. These alterations are costly, require significant resources, effort and take time.

Developing a prosthesis is a process that requires the input of many stakeholders (e.g. prosthetist and manufacturer) and requires the coordination of a complex set of activities. These stakeholders also have needs and constraints that change with time. There has been some research work (Colombo *et al.*, 2010; Sansoni, Wodehouse and Buis, 2015) carried out to address how the design and development of prosthesis can be improved, however this tends to focus on only the current rather than the evolving amputee needs.

The research reported in this paper is aimed at precisely addressing the question on how a cost-effective Prosthesis Development Service (*PDS*) Framework can be prescribed to cater for both the ***current*** and ***evolving*** needs of amputees whilst concurrently considering (Borg, Yan and Juster, 2000) the co-evolving needs of the other stakeholders such as prosthetists and standard system part manufacturers. The hypothesis of our research group has been that "by developing a smart modular prosthesis design structure that can be configured for the needs of different amputees through a product-service system, the aftercare provided to amputees will collectively improve". In this respect, our research has developed a ***prescriptive*** framework of an Amputee Healthcare Service System (called adProLiSS) that ***adapts to an amputee's evolving needs***. This paper shall disclose how AI concepts enable this framework and will be demonstrated through the implementation and evaluation of a prototype called PREMIER that takes above the knee amputations as a case-study.

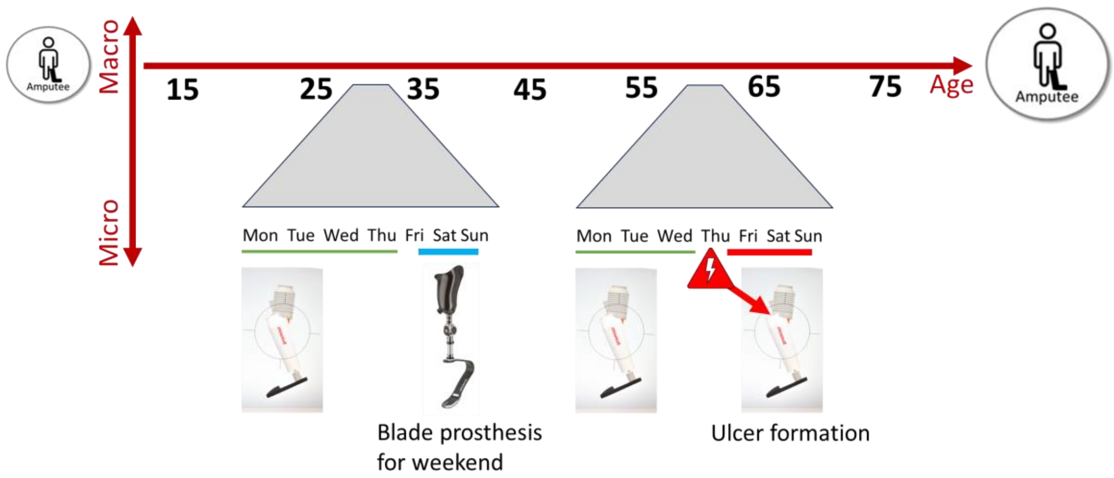

Figure 1. Evolution of amputee needs

2. State of the art product service systems for amputee healthcare

Product Service Systems (*PSS*) approaches are typically used in consumer products and services (Tukker, 2004; Tan and McAloone, 2006; Baines *et al.*, 2007; Ceschin, 2014; Ceschin *et al.*, 2014; Song and Sakao, 2017; Hein *et al.*, 2018) where the manufacturers tend to solely focus on the use phase. Additionally, users are not directly involved or consulted during the different phases. This has been shown by (Yang, Xing and Lee, 2010; Yang and Xing, 2014; Szwejczewski, Goffin and Anagnostopoulos, 2015; Shokouhyar, Shokoohyar and Safari, 2020; Gaiardelli *et al.*, 2021; Nemoto, Dhiman and Röcker, 2021) which outlines that the user's input is only considered in a single life-phases and that only the users current needs are considered. This has similarly been found with PSS approaches that are used in healthcare services (Mittermeyer, Njuguna and Alcock, 2011; Stacey and Tether, 2014; Pourabdollahian and Copani, 2015; Yip, Phaal and Probert, 2015; Xing, Rapaccini and Visintin, 2017). This means that the feedback from the user to the designer has so far been provided by chance. Additionally, our research team has continued to delve into PSS approaches in healthcare that exploit AI. Our findings have shown that there is research being done in the filed of AI in rehabilitation (Davenport and Kalakota, 2019; Neuhüttler *et al.*, 2020; Preidel and Stark, 2021; Aranda-Muñoz *et al.*, 2022; Mennella *et al.*, 2023) and AI in prosthetics and orthotics (Mai and Commuri, 2013; Kidziński *et al.*, 2019; Nayak and Kumar Das, 2020; Vélez-guerrero, Callejas-cuervo and Mazzoleni, 2021; Vélez-Guerrero, Callejas-Cuervo and Mazzoleni, 2021). To date, no explicit PSS literature (with or without the use of AI) concerning amputee aftercare, their evolving needs or the manufacture, distribution, ownership and use of prosthetics has been found. This has left a significant research gap (Figure 2) that our prescriptive framework adProLiSS can exploit.

https://doi.org/10.1017/pds.2024.221 Published online by Cambridge University Press

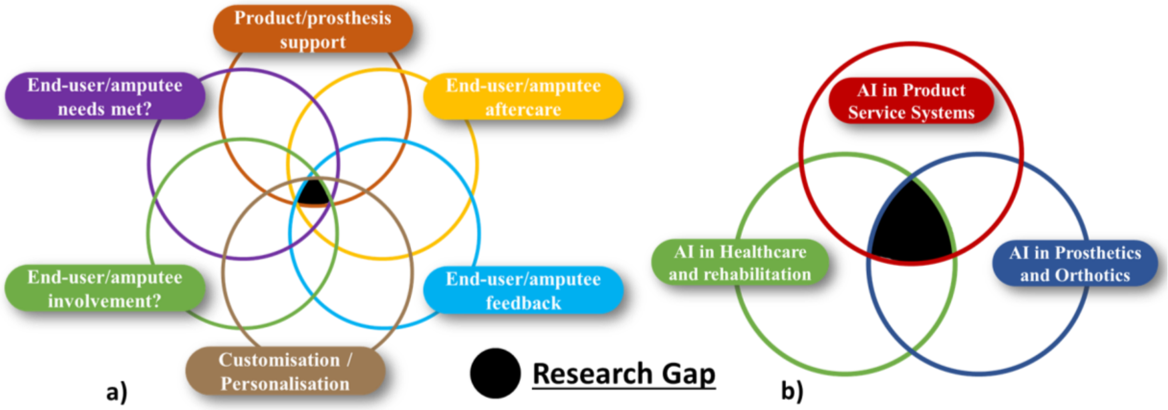

Figure 2. Research gaps: a) in PSS; b) in AI related fields of PSS and amputee healthcare

3. adProLiSS: a prescriptive and adaptive prosthesis development service framework

The adProLiSS Framework (Figure 3 and detailed in (Patiniott, Borg, *et al*., 2023)) has been developed to be both prescriptive and adaptive in nature, considering the customisation and personalisation of an amputee's prosthesis, and ensuring that the amputee's evolving needs are catered for. To achieve this, the adProLiSS Framework has been designed as a template for key Healthcare Managers which will allow them to further modify the framework to improve amputee aftercare within their healthcare institution. This will allow the different stakeholders (e.g. amputee, prosthetist, physiotherapist) to make use of the various features offered by the adProLiSS Framework with the sole purpose of improving the amputee's aftercare. The adProLiSS Framework is based on the IPD Model (Andreasen and Hein, 2000), with the Manufacturing (and assembly) pillar represented by the blue arrows; the Design pillar represented by the red arrows and the Healthcare Service Business represented by the green arrows. Additionally, the adProLiSS Framework is divided into three frames: 1) The Standard System Development Frame; 2) The Custom Prosthesis Development Frame; 3) The Prosthesis Adaptation Frame.

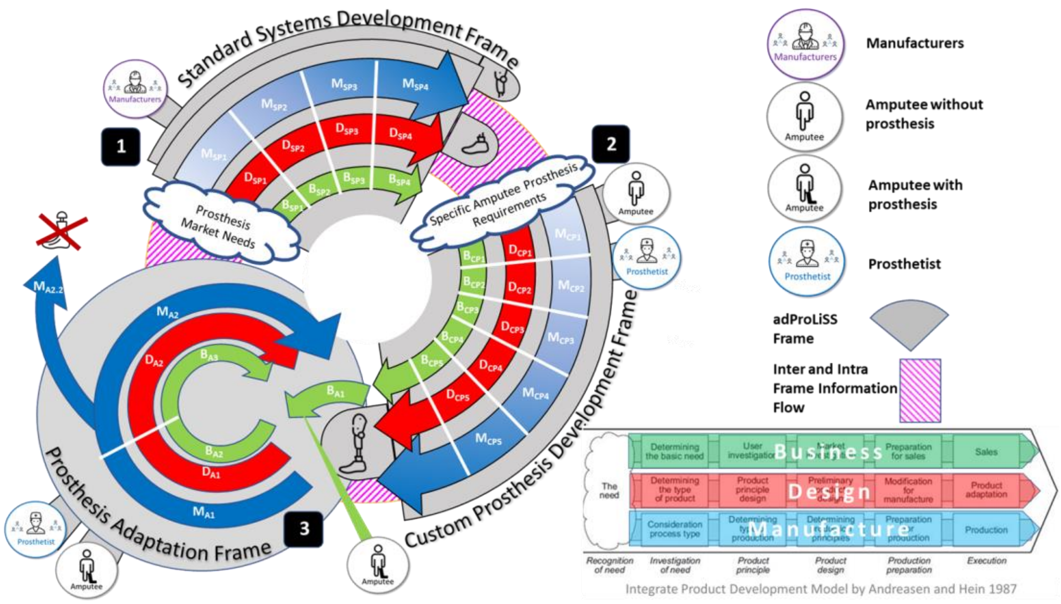

Figure 3. The adProLiSS framework

The Standard Systems Development Frame is made up of an accumulation of frames, with the output of each frame being a standard system (e.g. knee or ankle) and represents the process used by the established standard system manufacturers. Here the manufacturers must determine what the prosthesis

https://doi.org/10.1017/pds.2024.221 Published online by Cambridge University Press

market needs, determine the type of product that they wish to produce, manufacture and sell said product.

The Custom Prosthesis Development Frame is where prosthetists closely work with the amputee to obtain an understanding of the amputee's needs. Once the amputee's needs have been determined, the prosthetist will then select standard system parts that best suit the amputee's needs and place an order to obtain them. The prosthetist will then measure the amputee's residual limb and proceed to make the personalised socket. Once all the system parts (standard and personalised) are ready and available, the prosthetist will then assemble the prosthesis. The amputee will then try out their prosthesis to see if any alterations need to be made.

The Prosthesis Adaptation Frame is where our research team focus lies since this frame is concerned with providing an aftercare service to maintain the health of the amputee and the prosthesis. This is achieved by closely monitoring the amputee and prosthesis ***after*** the prosthesis has been given to the amputee. By means of a smart prosthesis with embedded sensors, key data (e.g. socket pressure, gait speed, step count) can be continuously recorded, processed into useful information and transmitted. This up-to-date information is then made available to the stakeholders (e.g. prosthetist and amputee) at any time. The strength of the Adaptation Frame is that it can evolve and adapt to cater for the ever changing and evolving needs of the amputee, which is only made possible due to the Inter and Intra Frame Information Highway.

4. Prototype adProLiSS implementation

To evaluate and experiment with the adProLiSS Framework, our research team has implemented a prototype Above Knee Prosthesis (*AKP*) system that focuses on the Adaptation Frame, called PREMIER. The implementation of PREMIER is based on three layers (Figure 4): 1) The Prosthesis Service Application Layer; 2) The Knowledge Layer; 3) The Physical Layer.

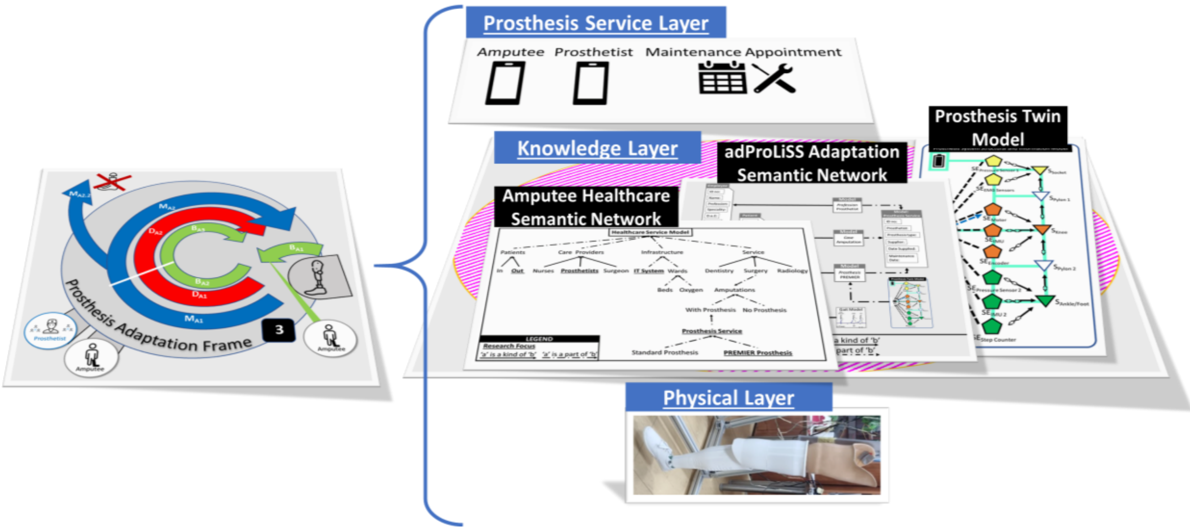

Figure 4. PREMIER Implementation

4.1. adProLiSS prosthesis service application layer

The adProLiSS Prosthesis Service Layer is where the interaction between the stakeholders (e.g. amputee, prosthetist) interact with the framework. This enables the healthcare providers to define what type of services and aftercare the amputee requires based on the information that is automatically provided (e.g. when excessive socket pressure is detected, and the probability of an ulcer is high, the prosthetist, administration and amputee will be informed, each with a detailed customised message).

4.2. adProLiSS knowledge layer

The adProLiSS Knowledge Layer defines the different types of knowledge required to provide an amputee aftercare service, including knowledge of what makes up a prosthesis digital twin; it consists of declarative knowledge to describe the healthcare system and procedural knowledge which infers decisions and actions to be taken depending on the amputee/prosthesis conditions. The Knowledge Layer consists of: a) The Patient Healthcare Service Semantic Network; b) the Amputee Adaptation Relational Network; c) The adProLiSS Intelligent Knowledge Base System.

4.2.1. The patient healthcare service semantic network

The healthcare service is a large entity that encompasses a multitude of different elements (e.g. medical staff, patients, services and infrastructure) that need to be mapped. Some of these elements interact with each other in a variety of ways. While it is important for a healthcare service to have a full detailed map of all the elements, our research focuses on the healthcare services related to amputees. Thus, the Patient Healthcare Semantic Network (Figure 5) outlines a Healthcare Service Model containing the elements related to amputee's care, both before amputation and after amputation. For this research purpose, we are focusing on the after-amputation interactions with the healthcare service, such as the amputees (out-patients), the prosthetists, the IT system (database), the prosthesis service and the prosthesis itself.

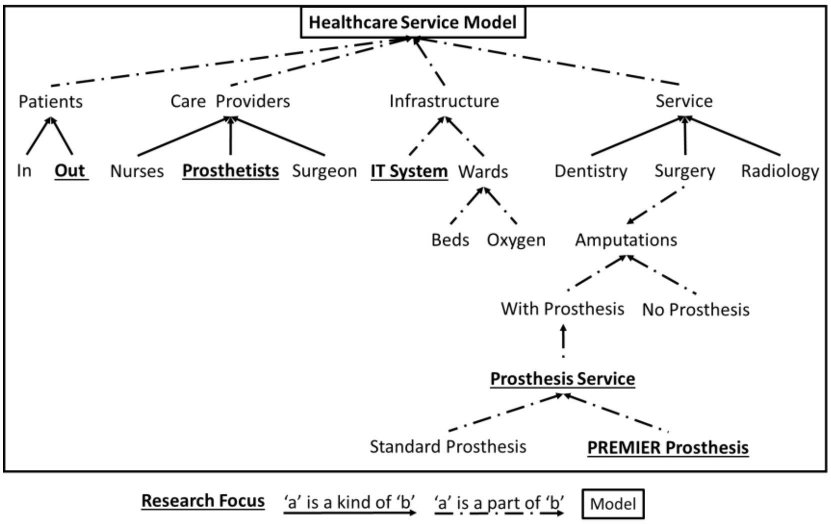

Figure 5. Patient healthcare service semantic network

4.2.2. The amputee adaptation relational network

Within the Patient Healthcare Service there are many different elements that interact with one another. The different relationships between the key elements of this network (e.g. prosthetist, patient, IT System) are detailed in Figure 6.

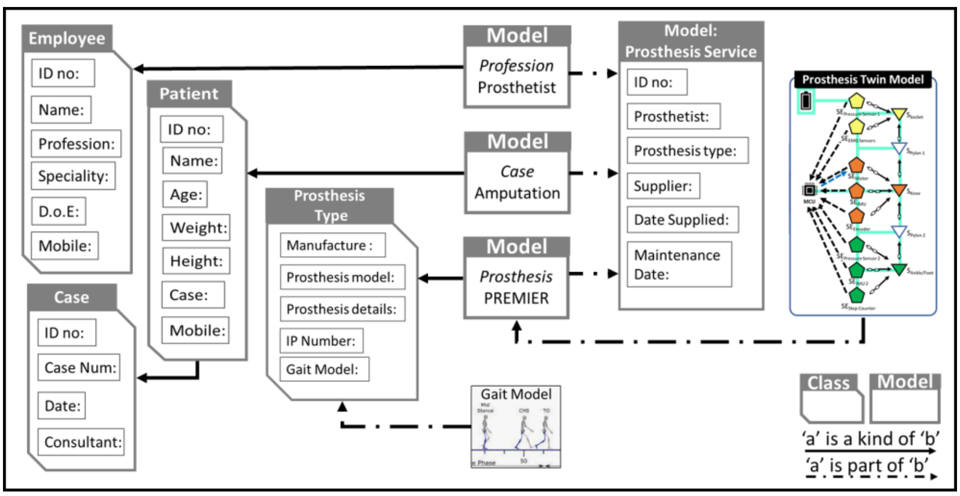

Figure 6. Amputee adaptation relational network

https://doi.org/10.1017/pds.2024.221 Published online by Cambridge University Press

When a patient's file is accessed, detailed patient information can be viewed, including their name, age and the different procedures (Cases) that they have been through. In the case of an amputee, the patient's file is linked to the Prosthesis Service Model, containing the Prosthesis Type that the amputee is using. The type of prosthesis can either be a standard prosthesis or the PREMIER prosthesis (Figure 7c). Unlike standard prosthesis, the PREMIER Prosthesis is a smart prosthesis that has embedded sensors that actively collect and transmit key prosthesis and residual limb data (e.g. socket pressure and gait speed), and process it into useful facts that can be processed by the adProLiSS Intelligent Knowledge Base System.

4.2.3. PREMIER twin model

The PREMIER Twin Model is a digital representation of the physical structure of the PREMIER prosthesis, its embedded sensors and flow of data being carried from the sensors to the Microcontroller (*MCU*) embedded within the prosthesis. The PREMIER digital twin model (Figure 7a) is based on our work carried out in (Patiniott, Vella, *et al.*, 2023).

4.2.4. adProLiSS intelligent knowledge base system

By making use of a smart prosthesis, such as the PREMIER prosthesis, that is equipped with embedded sensors, key data (e.g. voltage and pressure) can be continuously monitored and collected. This key data would be stored on the local MCU housed within the smart prosthesis. The adProLiSS Intelligent Knowledge Base System (*aIKBS*) is then able to access the accumulation of key data (now referred to as facts) and compare the current facts to the predefined facts stored within the Knowledge Base (*KB*) (Sarker, 2022). The facts stored within the KB will consist of the facts that pertain to the optimal performance of the prosthesis, the services provided by the healthcare professionals and the members (e.g. healthcare professionals, amputee) that are involved. Once a comparison has been made between the current facts and the predetermined facts within the KB, the aIKBS then infers new facts and then issues commands and actions to be taken based on a predefined set of rules. This process is shown in Figure 7b.

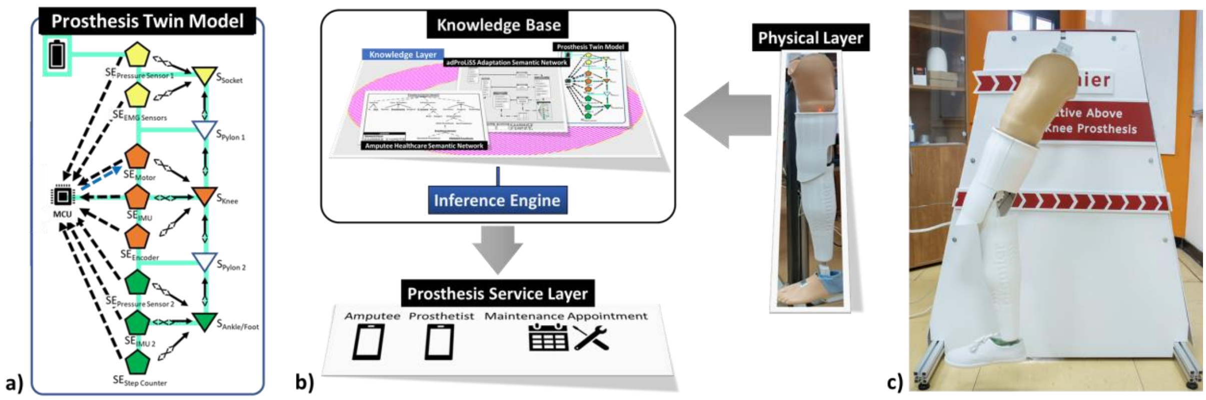

Figure 7. a) PREMIER digital twin model; b) aIKBS; c) PREMIER prosthesis

The aIKBS can be implemented using supervised machine learning techniques (Nasteski, 2017; Sarker, 2022) and makes use of various representation techniques, such as Logic-based representations, Semantic Networks, Rule-based Systems and Ontologies (Grimm, 2010; Yang, Zhuang and Pan, 2021) to enable the prosthesis to learn; for instance, amputee walking habits as time passes. For our short-term prototyping experimental purposes, we have employed a knowledge base system with a set of declared production rules. Consider for instance the rules R_i:

R_1 = If |Current socket pressure| < |Normal socket pressure|
THEN Continue monitoring the socket pressure
R_2 = If |Current socket pressure| > |Normal socket pressure|
THEN Continue monitoring the socket pressure
AND Access amputee data and send customised alert to amputee
AND Access prosthetists data and send customised alert to prosthetist
AND Access administration personnel and book appointment

https://doi.org/10.1017/pds.2024.221 Published online by Cambridge University Press

While the socket pressure is just one example, the aIKBS can be used for a variety of aftercare support scenarios, provided that the inference knowledge of different amputee healthcare situations are extensively defined.

4.3. adProLiSS physical layer

The adProLiSS Physical Layer is essentially made up of the PREMIER Prosthesis (Figure 7c) and is a prototype smart prosthesis that has been designed and assembled by our research team. As stated in the beginning of Section 4, the PREMIER Prosthesis houses several embedded sensors to facilitate the collection of key facts (e.g. pressure, speed, impact), which are used to monitor, maintain and improve the general health of the prosthesis and the amputee's residual limb. The Inter and Intra Information Highway is a key element that facilitates the flow of information. In addition, to provide intelligent feedback to the healthcare professionals as well as the amputees, the physical layer will also incorporate a microcontroller which will be the brains by which the smart prosthesis operates the overall amputee adaptation service. The design of the PREMIER prosthesis allows for modifications to be easily made such that additional sensors may be added, as well as modification of components.

5. Discussion

Our research team performed an internal experiment to test the adProLiSS Framework, Figure 8 showing the procedures taking place within each frame.

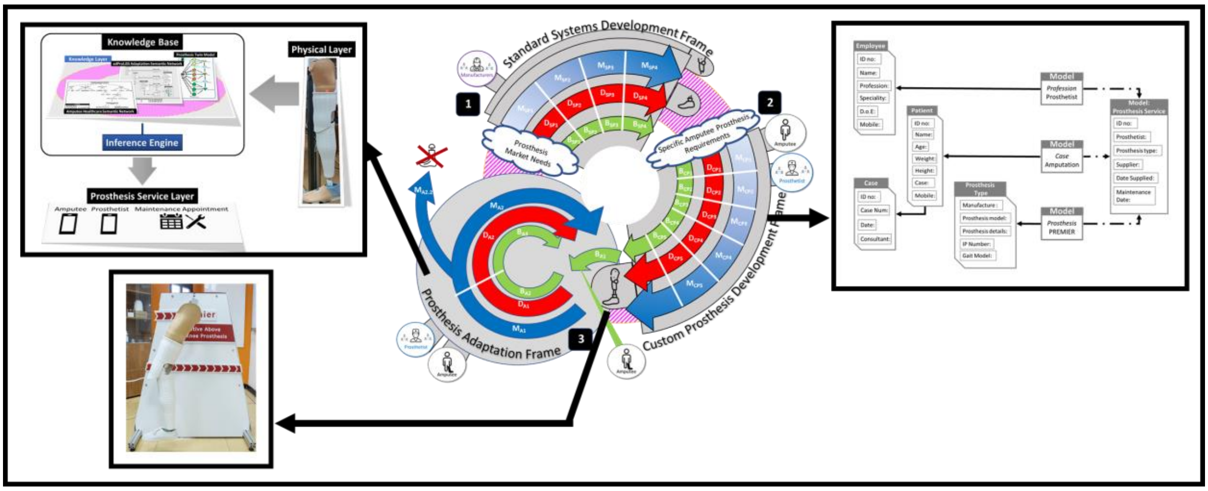

Figure 8. adProLiSS framework procedural knowledge

A scaled down knowledge base was created to simulate the adProLiSS Adaptation Semantic Network. Here two team members (one pretending to be the prosthetist and the other the amputee) entered their details, including their smartphone contact details. Gait data of the 'amputee' was recorded and programmed into the MCU within the prosthesis. A manual control mechanism was set up to allow the 'amputee' to change the gait speed at will, simulating different walking patterns. Two pressure sensors were attached to the prosthesis, one in the socket and the other at the base of the foot, their sensitivity being calibrated accordingly. This information was also stored within the knowledge base. Once the physical system was activated, the aIKBS continuously monitored the gait speed and the pressure values (facts) obtained from both pressure sensors. The 'amputee' would then vary the gait speed at will while another team member would apply pressure to the pressure sensors at random to simulate an ulcer formation. The inference engine of the aIKBS continuously compared the current pressure value to that value stored within the KB. When the inference engine found the current pressure value to be higher than the nominal value stored within the KB, then the inference engine executed rule R_2 to send a message to the amputee and prosthetist by obtaining the contact information stored as part of their declarative knowledge and sent the customised message to their smartphone. These custom messages contained the time, the gait speed and where (socket or foot) the excessive pressure was detected. In the

https://doi.org/10.1017/pds.2024.221 Published online by Cambridge University Press

case of the 'amputee', an additional message was sent instructing the 'amputee' to alter activities to reduce the chance of further pressure issues.

6. Conclusion

The prescribed adProLiSS framework is intended to result in an improved aftercare service to amputees. Due to its different frames, the framework is relevant to different stakeholders in different ways. The *Standard Systems Development Frame* is intended to guide manufacturing entities of standard prosthesis parts on what subsystems are required to result in a functional and smart prosthesis. The *Custom Prosthesis Development Frame* is intended to guide how and when prosthetists can involve amputees so that they co-design a user-specific smart prosthesis. On the other hand, the *Prosthesis Adaptation Frame* is intended for use by health service managers/policy makers as it outlines how prosthetists and other health care professionals such as physiotherapists can through a smart prosthesis provide amputees with an improved service that caters for the evolving needs of amputee. Overall, the framework also discloses how health system managers can practically implement such an adaptive service through the Inter and Intra Frame Information Highway. This of course assumes that due to GDPR (Li, Yu and He, 2019) amputees provide permission for data of their daily activities and prosthesis related issues to be recorded. The frequency by which such data should be collected and transmitted can give rise to 'big data'(Fan, Han and Liu, 2014; Oussous et al., 2018) challenges, this implying further research in this respect. At the same time, the availability of big data highlights how the adProLiSS Framework can be used through AI concepts to analyse patterns and trends in prosthesis use to assist (a) healthcare professionals to swiftly detect and be informed of amputee health issues (e.g. formation of ulcers in certain specific areas of the socket) and (b) to guide prosthesis manufacturers in improving future prosthesis design solutions. In this respect, the aIKBS concepts presented provides IT experts with an outline of the type of knowledge that needs to be captured and modelled to allow future healthcare systems to provide amputees with an adaptive aftercare service. Based on feedback obtained from demonstrations and preliminary evaluations, it is clear that the prescribed adProLiSS framework contributes an important step towards a healthcare service that adapts for the evolving needs of amputees that merits further research.

Currently, the aIKBS uses rules that map the input facts received from the smart prosthesis to desired outputs. In future, the aIKBS can be further improved by making use of unsupervised machine learning techniques, generating an AI that is able to uncover hidden data patterns from the incoming facts and correctly infer the right instructions and actions that need to be taken without any form of supervision (Nasteski, 2017; Sarker, 2022).

Acknowledgements

The research reported in this paper is funded through ERDF.01.124 as part of the project PREMIER – Development of a Low-Cost Product-Service System for a Smart and Modular, Emotionally Pleasing Above Knee Prosthesis.

References

Andreasen, M. and Hein, L. (2000) 'Integrated Product Development', *IPU, Lundtofte* [Preprint].

Aranda-Muñoz *et al*. (2022) 'Co-Designing with AI in Sight', in *Proceedings of the Design Society*. Cambridge University Press, pp. 101–110. Available at: https://doi.org/10.1017/pds.2022.11.

Baines, T.S. *et al.* (2007) 'State-of-the-art in product-service systems', *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 221(10), pp. 1543–1552. Available at: https://doi.org/10.1243/09544054JEM858.

Borg, J.C., Yan, X.T. and Juster, N.P. (2000) 'Exploring decisions' influence on life-cycle performance to aid "design for Multi-X"', *AI EDAM*, 14(2), pp. 91–113. Available at: https://doi.org/10.1017/S0890060400142015.

Casciato, D.J. *et al.* (2023) 'Diabetes-Related Major and Minor Amputation Risk Increased During the COVID-19 Pandemic', *Journal of the American Podiatric Medical Association*, 113(2). Available at: https://doi.org/10.7547/20-224.

Ceschin, F. (2014) ‘Product-service system innovation: A promising approach to sustainability’, *SpringerBriefs in Applied Sciences and Technology*, 17, pp. 17–40. Available at: https://doi.org/10.1007/978-3-319-03795-0_2/COVER.

Ceschin, F. *et al.* (2014) *Visualising product-service system business models*. Available at: https://www.researchgate.net/publication/279930520_Visualising_product-service_system_business_models (Accessed: 10 July 2023).

Colombo, G. *et al.* (2010) ‘A new design paradigm for the development of custom-fit soft sockets for lower limb prostheses’, *Computers in Industry*, 61(6), pp. 513–523. Available at: https://doi.org/10.1016/J.COMPIND.2010.03.008.

Davenport, T. and Kalakota, R. (2019) *DIGITAL TECHNOLOGY The potential for artificial intelligence in healthcare*, *Future Healthcare Journal*.

Eidmann, A. *et al.* (2023) ‘Demographics and Etiology for Lower Extremity Amputations—Experiences of an University Orthopaedic Center in Germany’, *Medicina (Lithuania)*, 59(2). Available at: https://doi.org/10.3390/medicina59020200.

Fan, J., Han, F. and Liu, H. (2014) ‘Challenges of Big Data analysis’, *National Science Review*. Oxford University Press, pp. 293–314. Available at: https://doi.org/10.1093/nsr/nwt032.

Gaiardelli, P. *et al.* (2021) ‘Product-service systems evolution in the era of Industry 4.0’, *Service Business*, 15(1), pp. 177–207. Available at: https://doi.org/10.1007/s11628-021-00438-9.

Grimm, S. (2010) ‘Knowledge Representation and Ontologies’, *Scientific Data Mining and Knowledge Discovery: Principles and Foundations*, pp. 1–400. Available at: https://doi.org/10.1007/978-3-642-02788-8.

Hein, A.M. *et al.* (2018) ‘Product service system design in a system of systems context: A literature survey’, in *Proceedings of International Design Conference*, *DESIGN*. Faculty of Mechanical Engineering and Naval Architecture, pp. 2891–2902. Available at: https://doi.org/10.21278/idc.2018.0358.

Jennifer Spector, B. and Editor, A. (2020) ‘Studies Note Increase In Amputations After Arrival Of COVID-19 Pandemic’, *Annals of Vascular Surgery*, October. Available at: https://www.hmpgloballearningnetwork.com/site/podiatry/studies-note-increase-amputations-after-arrival-covid-19-pandemic.

Kidziński, Ł. *et al.* (2019) ‘Artificial Intelligence for Prosthetics - challenge solutions’. Available at: http://arxiv.org/abs/1902.02441.

Li, H., Yu, L. and He, W. (2019) ‘The Impact of GDPR on Global Technology Development’, *Journal of Global Information Technology Management*. Taylor and Francis Inc., pp. 1–6. Available at: https://doi.org/10.1080/1097198X.2019.1569186.

Mai, A. and Commuri, S. (2013) ‘Intelligent control of a prosthetic ankle joint’, in *ICINCO 2013 - Proceedings of the 10th International Conference on Informatics in Control*, *Automation and Robotics*, pp. 17–25. Available at: https://doi.org/10.5220/0004485600170025.

Mennella, C. *et al.* (2023) ‘The Role of Artificial Intelligence in Future Rehabilitation Services: A Systematic Literature Review’, *IEEE Access*. Institute of Electrical and Electronics Engineers Inc., pp. 11024–11043. Available at: https://doi.org/10.1109/ACCESS.2023.3236084.

Mittermeyer, S.A., Njuguna, J.A. and Alcock, J.R. (2011) ‘Product-service systems in health care: Case study of a drug-device combination’, *International Journal of Advanced Manufacturing Technology*, 52(9–12), pp. 1209–1221. Available at: https://doi.org/10.1007/s00170-010-2766-4.

Nasteski, V. (2017) ‘An overview of the supervised machine learning methods’, *HORIZONS.B*, 4, pp. 51–62. Available at: https://doi.org/10.20544/horizons.b.04.1.17.p05.

Nayak, S. and Kumar Das, R. (2020) ‘Application of Artificial Intelligence (AI) in Prosthetic and Orthotic Rehabilitation’, in *Service Robotics*. IntechOpen. Available at: https://doi.org/10.5772/intechopen.93903.

Nemoto, Y., Dhiman, H. and Röcker, C. (2021) ‘Design for continuous use of product-service systems: A conceptual framework’, in *Proceedings of the Design Society*. Cambridge University Press, pp. 983–992. Available at: https://doi.org/10.1017/pds.2021.98.

Neuhüttler, J. *et al.* (2020) ‘Perceived quality of artificial intelligence in smart service systems: A structured approach’, *Communications in Computer and Information Science*, 1266 CCIS, pp. 3–16. Available at: https://doi.org/10.1007/978-3-030-58793-2_1/TABLES/1.

Oussous, A. *et al.* (2018) ‘Big Data technologies: A survey’, *Journal of King Saud University - Computer and Information Sciences*. King Saud bin Abdulaziz University, pp. 431–448. Available at: https://doi.org/10.1016/j.jksuci.2017.06.001.

Patiniott, N., Borg, J.C., *et al.* (2023) ‘ELEMENTS OF A PRESCRIPTIVE AND ADAPTIVE PROSTHESIS DEVELOPMENT SERVICE FRAMEWORK’, *Proceedings of the Design Society*, 3, pp. 1605–1614. Available at: https://doi.org/10.1017/PDS.2023.161.

Patiniott, N., Vella, P.C., *et al.* (2023) ‘Towards an Ontology For a Smart and Adaptive Prosthesis Service System Framework’.

Pourabdollahian, G. and Copani, G. (2015) ‘Development of a PSS-oriented business model for customized production in healthcare’, in *Procedia CIRP*. Elsevier B.V., pp. 492–497. Available at: https://doi.org/10.1016/j.procir.2015.02.158.

Preidel, M. and Stark, R. (2021) ‘Semdaserv: A systematic approach for semantic data specification of ai-based smart service systems’, *Applied Sciences (Switzerland)*, 11(11). Available at: https://doi.org/10.3390/app11115148.

Sansoni, S., Wodehouse, A. and Buis, A. (2015) *A new design system of below-limb prostheses The role of a visual prosthetic designer*. Available at: https://www.researchgate.net/publication/282576255_A_new_design_system_of_below-limb_prostheses_The_role_of_a_visual_prosthetic_designer (Accessed: 21 July 2023).

Sarker, I.H. (2022) ‘AI-Based Modeling: Techniques, Applications and Research Issues Towards Automation, Intelligent and Smart Systems’, *SN Computer Science*, 3(2). Available at: https://doi.org/10.1007/s42979-022-01043-x.

Shokouhyar, S., Shokoohyar, S. and Safari, S. (2020) ‘Research on the influence of after-sales service quality factors on customer satisfaction’, *Journal of Retailing and Consumer Services*, 56. Available at: https://doi.org/10.1016/j.jretconser.2020.102139.

Song, W. and Sakao, T. (2017) ‘A customization-oriented framework for design of sustainable product/service system’, *Journal of Cleaner Production*, 140, pp. 1672–1685. Available at: https://doi.org/10.1016/j.jclepro.2016.09.111.

Stacey, P.K. and Tether, B. (2014) *Designing Emotion--Centred Product Service Systems: the Case of a Cancer Care Facility*, *Working Paper series*. Available at: http://www.lums.lancs.ac.uk/publications.

Szwejczewski, M., Goffin, K. and Anagnostopoulos, Z. (2015) ‘Product service systems, after-sales service and new product development’, http://dx.doi.org/10.1080/00207543.2015.1033499, 53(17), pp. 5334–5353. Available at: https://doi.org/10.1080/00207543.2015.1033499.

Tan, A.R. and McAloone, T.C. (2006) ‘CHARACTERISTICS OF STRATEGIES IN PRODUCT/SERVICE-SYSTEM DEVELOPMENT’, *DS 36: Proceedings DESIGN 2006, the 9th International Design Conference, Dubrovnik, Croatia*, pp. 1435–1442. Available at: https://www.designsociety.org/publication/19156/CHARACTERISTICS+OF+STRATEGIES+IN+PRODUCT%2FSERVICE-SYSTEM+DEVELOPMENT (Accessed: 22 July 2023).

Tukker, A. (2004) ‘Eight types of product-service system: Eight ways to sustainability? Experiences from suspronet’, *Business Strategy and the Environment*, 13(4), pp. 246–260. Available at: https://doi.org/10.1002/bse.414.

Vélez-guerrero, M.A., Callejas-cuervo, M. and Mazzoleni, S. (2021) ‘Artificial intelligence-based wearable robotic exoskeletons for upper limb rehabilitation: A review’, *Sensors*. MDPI AG, pp. 1–30. Available at: https://doi.org/10.3390/s21062146.

Vélez-Guerrero, M.A., Callejas-Cuervo, M. and Mazzoleni, S. (2021) ‘Design, development, and testing of an intelligent wearable robotic exoskeleton prototype for upper limb rehabilitation’, *Sensors*, 21(16). Available at: https://doi.org/10.3390/s21165411.

Xing, K., Rapaccini, M. and Visintin, F. (2017) ‘PSS in Healthcare: An Under-Explored Field’, in *Procedia CIRP*. Elsevier B.V., pp. 241–246. Available at: https://doi.org/10.1016/j.procir.2017.03.068.

Yang, L. and Xing, K. (2014) ‘A concept innovation model for product service systems development and application’, pp. 1–6. Available at: https://doi.org/10.1109/ICSSSM.2014.6943401.

Yang, L., Xing, K. and Lee, S.H. (2010) ‘A new conceptual life cycle model for Result-Oriented Product-Service System development’, in *Proceedings of 2010 IEEE International Conference on Service Operations and Logistics, and Informatics, SOLI* 2010, pp. 23–28. Available at: https://doi.org/10.1109/SOLI.2010.5551621.

Yang, Y., Zhuang, Y. and Pan, Y. (2021) ‘Multiple knowledge representation for big data artificial intelligence: framework, applications, and case studies’, *Frontiers of Information Technology and Electronic Engineering*, 22(12), pp. 1551–1558. Available at: https://doi.org/10.1631/FITEE.2100463.

Yip, M.H., Phaal, R. and Probert, D.R. (2015) ‘Characterising product-service systems in the healthcare industry’, *Technology in Society*, 43, pp. 129–143. Available at: https://doi.org/10.1016/j.techsoc.2015.05.014.

Young, M. *et al.* (2019) ‘Time-related changes in quality of life in persons with lower limb amputation or spinal cord injury: protocol for a systematic review’, *Systematic reviews*, 8(1). Available at: https://doi.org/10.1186/S13643-019-1108-3.