Institution: King's College London

Unit of Assessment: Computer Science and Informatics (UoA 11)

Title of case study: Healthcare and commercialization impact through innovative technologies for robotic rehabilitation

Period when the underpinning research was undertaken: 2000-2019

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Jian S. Dai	Professor	1999 - present

Period when the claimed impact occurred: 2016 – 2020

Is this case study continued from a case study submitted in 2014? N

1. Summary of the impact (indicative maximum 100 words)

Research led by Professor Jian Dai on the design of robot manipulators has led to the development of robotic therapy devices for the treatment of lower limb injuries. Two companies have been founded to develop cutting-edge healthcare technologies based on this research: Movendo Technology (Italy), a large biomedical company which provides rehabilitation devices and effective rehabilitation treatment, and AiTreat Pte Ltd. (Singapore), a cutting-edge robotic massage start-up.

An independent evaluation has found that the robotic devices developed by these companies provide treatment equal to or better than conventional physiotherapy, but at lower cost and more reliable consistency, in particular for diagnosing susceptibility to falls in older people, rehabilitation for patients with Parkinson's disease after spinal injury and stroke, and rehabilitation after lower limb trauma.

In total, more than 11,000 patients have been treated with these robotic devices at over 100 clinics and hospitals in countries including Singapore, Italy, Germany, Czech Republic, Netherlands, Spain, US, Dubai, Canada, Greece, Saudi Arabia, Puerto Rico, Switzerland and Ukraine. Over 800,000 physiotherapy treatments have been delivered.

Movendo Technology has 34 employees and 1,500 agents worldwide, and its annual turnover was EUR2,764,000 in 2019. Its market share is approximately 2%. AiTreat has completed three rounds of VC/Pharma funding, and its 2019 turnover was USD460,000, 60% of which is attributed to Prof. Dai's technology.

2. Underpinning research (indicative maximum 500 words)

Professor Jian Dai has been working on the mechanism design and orientation and dexterity of robot manipulators ever since he joined King's College London in 1999. His research, conducted together with his PhD students, post-doctoral researchers and collaborators, has included both fundamental contributions on relevant modelling and computing methodologies and development of applications in various contexts. This has led to designing novel technologies for rehabilitation and massaging robots. The development and utilization of such robots by Movendo (rehabilitation robots) and AiTreat (massaging robots) are the subject of this impact case study (ICS).

Dai's research underpinning this ICS began in the early 2000s with theoretical work on computational procedures for kinematics and control theory. Dai and Rees Jones [R1] presented a new approach for constructing the null space of a linear system of homogeneous equations using the cofactors of an augmented coefficient matrix. Their approach improved on the computational efficiency of the previous methods, by avoiding the Gauss–Seidel elimination algorithm, and on their numerical accuracy. [R1] showed how the new method can be applied in kinematics to calculate reciprocal screw systems, providing a theoretical framework for analysis and synthesis of robotic mechanisms.

Dai et al. [R2] used the method from [R1] in designing robotic platforms for ankle rehabilitation and analysing their stiffness. The proposed devices had fewer degrees of

freedom than the competing designs, hence fewer actuators and simpler control leading to reduced costs. From the technological viewpoint, the devices integrated various stages of rehabilitation and could be tailored to requirements of physiotherapy. The results from [R2] provided technology for the development of robotic rehabilitation systems by Movendo.

Saglia et al. [R3] proposed control algorithms for redundantly actuated parallel mechanisms. The algorithms were based on inverse kinematics, relied on the accuracy of the proposed mathematical models and numerical procedures for Jacobian matrices, and were calibrated and validated in simulations and experiments. The control algorithms in [R3] together with the prototype presented in [R4] provided, via the patent US20110306473, the basis for the final design of the Movendo Hunova robotic platform.

The analysis of the relationship between force and motion initiated in [R1] was used in Zhang et al. [R5] in design and analysis of extensible continuum robots, and was further extended in Cui et al. [R6] for finger-rolling contact analysis. [R5] and [R6] laid foundations for the inverse kinematics formulated as a system of nonlinear algebraic equations in terms of the joint rates of the finger linkage mechanism and the parameters of the contact trajectories. This work provided the basis for designing the massaging device at AiTreat.

Li et al. [R7], starting again from the results presented in [R1], proposed a novel model-free method based on the adaptive Kalman filter to achieve path tracking for a continuum robot using only pressures and tip position. As the Kalman filter requires only a two-step algebraic calculation per one control interval, the low computational load and the real-time control capability were achieved. Simulations and experimental validation showed robustness of this control method against system uncertainties. This work was used by AiTreat in implementing control in their robotic devices.

The research underpinning this ICS as described above was supported by EPSRC and EU grants and attracted sponsorship from THK Co. Ltd. Japan for the investigation into robotic massage fingers. The current EPSRC grant EP/S019790/1, awarded jointly to King's College London and Leeds University, extends further this research, aiming at development of new robotic healthcare devices. Jian Dai received the 2015 ASME Mechanisms and Robotics Award and the 2020 ASME Machine Design Award for his lifelong contribution to the fundamental theory, design and applications of mechanisms and robotics systems.

3. References to the research (indicative maximum of six references)

[R1] **Dai, JS** & Rees Jones, J 2002, 'Null-space construction using cofactors from a screw-algebra context', Royal Society of London. Proceedings A. Mathematical, Physical and Engineering Sciences, vol. 458, no. 2024, pp. 1845 - 1866. https://doi.org/10.1098/rspa.2001.0949

[R2] **Dai, JS**, Zhao, T & Nester, C 2004, 'Sprained ankle physiotherapy based mechanism synthesis and stiffness analysis of a robotic rehabilitation device', Autonomous Robots, vol. 16, no. 2, pp. 207 - 218. https://doi.org/10.1023/B:AURO.0000016866.80026.d7

[R3] Saglia, JA, Tsagarakis, NG, **Dai, JS** & Caldwell, DG 2009, 'Inverse-kinematics-based control of a redundantly actuated platform for rehabilitation', PROCEEDINGS- INSTITUTION OF MECHANICAL ENGINEERS PART I JOURNAL OF SYSTEMS AND CONTROL ENGINEERING, vol. 223, no. I1, pp. 53 - 70. https://doi.org/10.1243/09596518JSCE622

[R4] Saglia, JA, Tsagarakis, NG, **Dai, JS** & Caldwell, DG 2013, 'Control Strategies for Patient-Assisted Training Using the Ankle Rehabilitation Robot (ARBOT)', IEEE ASME TRANSACTIONS ON MECHATRONICS, vol. PP, no. 99, pp. 1-10. https://doi.org/10.1109/TMECH.2012.2214228

[R5] Zhang, K, Qiu, C & **Dai, JS** 2016, 'An extensible continuum robot with integrated origami parallel modules', Journal of Mechanisms and Robotics, vol. 8, no. 3, 031010. https://doi.org/10.1115/1.4031808

[R6] Cui, L, Sun, J & **Dai, JS** 2017, 'In-hand forward and inverse kinematics with rolling contact', Robotica, pp. 1-19. https://doi.org/10.1017/S026357471700008X

[R7] Li, M, Kang, R, Branson, DT & **Dai, JS** 2018, 'Model-free Control for Continuum Robots Based on an Adaptive Kalman Filter', IEEE ASME TRANSACTIONS ON MECHATRONICS, vol. 23, no. 1. https://doi.org/10.1109/TMECH.2017.2775663

4. Details of the impact (indicative maximum 750 words)

Two companies have been founded to exploit Prof. Dai's underpinning research: Movendo and AiTreat. In each company, one of the co-founders was a former research student of Prof. Dai. Each company has developed its own therapy robot. While much of the underlying research is similar, they use two quite different applications of robot technology with Movendo concentrating on a rehabilitation platform whereas the AiTreat robot delivers massage and acupuncture.

An independent evaluation has found that research at King's led directly, and via the careers of the two former students and the technology of the two firms, to high quality products which benefits thousands of patients globally per annum. The larger part of the underlying technology is directly attributable to King's research, although both firms also have added substantially to that core, for example in diagnostics and supporting clinical workflows, as well as extending clinical applications. However, it is unlikely that either firm would ever have been started or developed its technologies without the research inputs from King's. [S1, p.19]

Movendo: technology development, founding, investment and company growth

Research conducted by Prof. Dai and his then PhD student Dr Jody Saglia [R3] (based on [R1, R2]) led to a key patent. The work attracted investment of over EUR10,000,000 from the Italian National Institute for Insurance against Accidents at Work (INAIL), that was helping to develop the ankle rehabilitation device "Arbot" and ran a successful RCT (Randomised Control Trial) on orthopaedic post-traumatic patients with lower limb injuries. The clinical trial and the patent led to the development of a new device for total body rehabilitation, Hunova, based on the core technology of the ankle rehabilitation device "Arbot" and the Patent. Hunova was been developed and clinically validated at the Italian Institute of Technology by a team including Dr Saglia, who raised EUR10,000,000 in corporate venture funding from Dompé Pharmaceuticals, one of the main Italian biopharmaceutical groups [S7] to start a new company, Movendo Technology, in late 2016. [S2]

Movendo Technology acquired an exclusive license for the Arbot and Hunova technology and now operates globally to commercialise its solutions in the rehabilitation market. Hunova is Movendo Technology's principal product. It targets rehabilitation of the lower limbs, from ankle to knee and hip, the pelvis, and trunk, by providing a large variety of training modalities. [S6]

Movendo Technology Group employs 34 people (as of 31 July 2020), and annual turnover rose from EUR1,292,000 in 2017 to EUR2,764,000 in 2019. Its market share is approximately 2% [S11]. To date, it has sold 69 units. In addition to its core staff, Movendo employs around 1,500 agents worldwide. [S10]

In total, more than 10,000 patients have been treated at over 100 clinics and hospitals in countries including Italy, Germany, Czech Republic, Netherlands, Spain, US, Dubai, Canada, Greece, Saudi Arabia, Puerto Rico, Switzerland and Ukraine. Over 800,000 physiotherapy treatments have been delivered. [S11]

Dr Saglia, Movendo Technology, co-founder and former CTO [S2]:

> *"Prof. Dai's contribution has been significant along the entire journey - from the very beginning of the concept idea to the final product design passing through clinical validation. This is a clear example of world leading research being successfully transferred to the industrial world, making a real impact on society. [Today] Movendo is continuously fostering a research and technology development collaboration with Prof. Dai's group for its future products."*

AiTreat: Technology development, founding, investment and company growth

AiTreat Pte Ltd. (Singapore) has developed EMMA, a massage robot based on the technology proposed in [R5, R6, R7] by Prof. Dai and his PhD student, Chen Qiu. Following the receipt of an ACE Grant from SPRING Singapore (2015), the company has now completed three rounds of fundraising with the last round of investments coming from Brain Robotics Capital LP (a prestigious US VC), Tasly Pharmaceutical Group Co Ltd (Shanghai) and Ogawa Smart Healthcare Technology Group Co Ltd (Shenzhen). [S8]

> *"EMMA is AiTreat's primary development and the first successful one of its kind in the world. EMMA is a state-of-the-art soft tissue therapeutic treatment system that utilizes robotic technology and medical knowledge that is stored using Artificial Intelligence. […] EMMA is equipped with sensors to measure muscle stiffness and uses 3D vision technology to analyze the patient's body."* [AiTreat website, quoted in [S1, p.6]]

AiTreat Pte Ltd. has produced several generations of the massaging robot EMMA in four clinics in Singapore, with over 1,000 customers and over 5,000 times of use [S9]. The company turnover is USD460,000, 60% of which is due to using Prof. Dai's technology. [S9]

AiTreat Pte Ltd was the winner of the Microsoft Developer Day Start-up Competition (2016), winner of 'Best Product/Application Design Award' at Shanghai International Start-up Competition (2016), and recipient of a StartupSG Tech Grant from Enterprise Singapore (2017). [S8]

Benefits of the robotic systems to medical practitioners and patients

The key benefits cited by practitioners who use the robotic systems are [S1, p.9]:

- Treating more patients, with better health outcomes. *"Combining several types of fingering including thumbing, index fingering and palm motion in one for massaging to provide versatile massage treatments using one end-effector, multiple types of massage, ... what this does is improve efficiency, enabling a large number of treatments."* [CTO of AiTreat, quoted in [S1, p.16]]
- Cost savings for clinics and patients
- Treatment equal to the best physiotherapist, but cheaper and easier to reproduce consistently. *"Treatment from our robots is about equivalent to the best treatment from the best physiotherapist but the latter is unreliable, expensive and hard to reproduce. Some traditional treatments require two to three persons to implement."* [Director, Sales and Marketing, Movendo, quoted in [S1, p.16]]
- Consistent standard of treatment. *"For example, [… with traditional treatment …] we give them exercises, [some] people don't do it, or we prescribe some random massage, it helps for a few days. But maybe it [results in] a misalignment of ligaments. We prescribe sessions on Emma for the back, and then acupuncture, with very good results."* [CTO of AiTreat, quoted in [S1, p.16]]
- The flexibility of the robotic systems. *"Adaptability - we can change from simulating rubber bands to swimming in a pool with the flick of a switch"* [Director, Sales and Marketing, Movendo, quoted in [S1, p.9]]

The clinical efficacy of the Movendo devices is documented in published research as at least equivalent and sometimes better than conventional treatment, in particular for:

- Diagnosing susceptibility to falls in older people [S3]
- Rehabilitation for patients with Parkinson's disease, after spinal injury and stroke [S4]
- Rehabilitation after lower limb trauma [S5]

Clinicians report that patients respond favourably to the robot treatment. *"Patients are intrigued…They like the consistency and the [lack of] worry about who [they] will get. We get a lot of word of mouth; they bring their friends."* [AiTreat clinician, quoted in [S1, p.15]]

The independent evaluation concludes:

"The two firms provide robotic technology, based substantially on research from KCL, which is part of a wave of clinical robotics which is likely to massively influence or even revolutionise the way clinical massage and acupuncture are delivered, and may extend beyond those core applications." [S1, p.19]

5. Sources to corroborate the impact (indicative maximum of 10 references)

[S1] Independent evaluation by Impact Science: "Robotic rehabilitation and massage", November 2020.

[S2] Testimonial from Jody Saglia, former Head of Rehabilitation Technology Laboratory, Movendo Technology Group

[S3] Cella, A., de Luca, A., Squeri, V., Parodi, S., Vallone, F., Giorgeschi, A., … Pilotto, A. 2020 'Development and validation of a robotic multifactorial fall-risk predictive model: A one-year prospective study in community-dwelling older adults', *PLoS ONE*, *15*(6), 1–22. https://doi.org/10.1371/journal.pone.0234904

[S4] G. Marchesi et al., 2019 'Robot-based assessment of sitting and standing balance: preliminary results in Parkinson's disease', IEEE 16th International Conference on Rehabilitation Robotics (ICORR), Toronto, ON, Canada, 2019, pp. 570-576. https://doi.org/10.1109/ICORR.2019.8779387

[S5] Taglione, E., Catitti, P., D'Angelo, M. L., Squeri, V., Saglia, J., Sanfilippo, C., & De Michieli, L. 2018 'Proprioceptive and motor training using the high performance robotic device hunova: Protocol of a randomized, controlled trial in patients with lower limb post-traumatic conditions',. Annals of Physical and Rehabilitation Medicine, 61, e497–e498.https://doi.org/10.1016/j.rehab.2018.05.1158

[S6] Iandolo, R., Marini, F., Semprini, M., Laffranchi, M., Mugnosso, M., Cherif, A., De Michieli, L., Chiappalone, M. and Zenzeri, J. (2019) 'Perspectives and Challenges in Robotic Neurorehabilitation', Applied Sciences. MDPI AG, 9(15), p. 3183. https://doi.org/10.3390/app9153183

[S7] Corriere delle Sera article: "Medicine, robots and hi-tech skeletons – alliance between Dompé and Iit of Genoa" (in Italian), 25 July 2016

[S8] AiTreat website

[S9] Testimonial from Yizhong Zhang, CEO of AiTreat Pte Ltd

[S10] Movendo Technology website

[S11] Testimonial from Giuseppe Betti, CFO of Movendo Technology Group