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Global Spotlights

APOLLO: advanced magnetic probes for minimally invasive endovascular interventions

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Annually, cardiovascular disease (CVD) accounts for over 20.5 million fatalities globally, representing one-third of all deaths.[1] Notably, coronary artery diseases claim the lives of 3.8 million men and 3.4 million women each year. Moreover, ∼15 million individuals worldwide experience a cerebrovascular accident (stroke), resulting in 5.8 million fatalities each year.[2] In the Netherlands for instance, an estimated 730 000 individuals (4% of the population) encounter cardiovascular incidents related to coronary heart disease annually, with 120 000 individuals experiencing heart failure and 260 000 individuals suffering from atrial fibrillation.[3] This underscores the pressing need for effective diagnosis and treatment of CVDs.

The burden of CVD, including conditions like atrial fibrillation, atherosclerosis, chronic limb threatening ischaemia (CLTI) and coronary artery diseases, along with their pathophysiological links to brain disorders such as aneurysms and strokes, has been extensively documented. Regrettably, the organs affected by CVD are often delicate and situated in remote locations, posing significant challenges to traditional treatment approaches. In contemporary endovascular surgeries, the prevailing method entails manual catheterization aided by fluoroscopy. In these procedures, ensuring precise control over the proximity of surgical catheters to delicate brain, heart, and peripheral vascular tissues is paramount. While manual instruments offer manoeuvrability, their capabilities are constrained. Moreover, modern imaging techniques like fusion imaging is hard to implement, for instance in lower extremity revascularization procedures in CLTI patients. To address this, tendon-driven devices are employed to enhance dexterity. However, these devices are prone to accuracy issues and reach limitations attributed to friction, potentially resulting in instrument failure or arterial damage *in situ*, especially in extreme cases. Additionally, the use of contrast materials to improve soft tissue visualization may provoke adverse reactions like renal insufficiency. Unfortunately, numerous multimorbid and frail vascular patients remain untreated as they are considered to have too many comorbidities to undergo surgery, whereas endovascular interventions still have limited success rates. This is particularly alarming considering that more than one-third of CVD-related deaths occur within this patient group.

Over the last decade, magnetic actuation systems have exhibited significant promise in offering precise steering capabilities for endovascular interventions.[4,5] In particular, wireless magnetically actuated robotic instruments emerge as a promising alternative to manual or tendon-driven flexible instruments, as they allow for miniaturization and eliminate the need for moving mechanical elements.[6] These magnetic surgical instruments incorporate magnetic components controlled by external magnetic field generators (*Figure 1*). The principles behind this approach have been extensively explored at the Surgical Robotics Laboratory, resulting in the creation of a variety of innovative magnetic probes designed for advanced minimally invasive surgery.

Among others, robotic instruments have been developed that utilize magnetic interactions for steering through tortuous vessels, wirelessly controlled to treat arterial stenoses, and launch and capture projectiles for targeted drug delivery.[7,8] Through these developments, small-scale robotic instruments have been shown to be capable of manipulation and operation in very confined spaces within the human body, a feat unachievable through manual or tendon-driven actuation methods.

An important conclusion drawn from this research pertains to the performance of magnetically actuated instruments within external fields, a factor critical for both precision and dexterity. Specifically, the navigational efficacy of magnetically actuated instruments hinges on their flexibility, magnetic characteristics, and the external field's strength. The intensity of an external field diminishes rapidly from its source, presenting a significant challenge from a robotic perspective in terms of power consumption and size of the operative system. From a clinical perspective, this poses challenges related to patient safety, but also for the set-up in angio suites and hybrid vascular operating theatres, and particularly in obese patients who are at higher risk of CVD.

There are currently a few commercial magnetic navigation systems on the market for clinical use. Prominent examples include the Levita® Magnetic Surgical System (Levita Magnetics, USA) predominantly used to control atrial fibrillation and laparoscopic cholecystectomy instruments, and the Niobe® and Genesis® (Stereotaxis Inc., USA) robotic

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Figure 1 APOLLO concept: a collection of robotically positioned magnets *ex vivo* accurately steer a magnetically actuated probe to the target location *in vivo*. An experimental probe design is shown in the bottom right corner, comprising multiple interacting permanent magnets and magnetic polymers.[7] APOLLO will develop robust hardware and software to guide dextrous probes for minimally invasive endovascular interventions

Figure 2 A pre-clinical magnetic actuation system by Flux Robotics B.V., comprising of a robot arm and electromagnet. A surgeon (left) steers a magnetic guidewire in an aortic phantom by hand-guiding the Flux One™ robot and manipulating the electrical current through the electromagnet, during a simulated fenestrated endovascular aortic aneurysm repair (f-EVAR) intervention

magnetic navigation systems predominantly used to treat atrial fibrillation, via a console operator, respectively. However, the latter navigation systems rely on large permanent magnets, which necessitate significant dedicated floor space. Moreover, clinicians require specialized training to operate the magnetic system effectively. From a robotics standpoint, these systems exhibit suboptimal performance, offering limited field-shaping capabilities and low control bandwidth. In terms of viability, these systems are not cost-effective, given the restricted number of interventions for which they are utilized. More critically, since such interventions are time-consuming, both clinicians and patients face substantial X-ray exposure, heightening the risk of cancer. Moreover, traditional designs of magnetically actuated instruments often compromise flexibility for magnetic properties, limiting instrument magnetization and imposing additional demands on the magnetic navigation system, which directly affects probe size. Considering these factors, enabling the downsizing of magnetic navigation systems by enhancing the magnetic properties and flexibility of the instruments has the potential to revolutionize magnetically assisted diagnostic and therapeutic interventions.

The APOLLO solution

Integrating clinically relevant magnetic actuation systems with multifunctional magnetic probes promises numerous advantages for both patients and clinicians. This integration is poised to broaden the scope of magnetically driven interventions by reducing the overall procedural duration for standard CVD treatments, as well as facilitating the clinical implementation of advanced instrument designs. To address this need, the *APOLLO* project proposes the development of the *Advanced magnetic PrObes for minimaLLy invasive endovascular interventions*. The APOLLO system (*Figure 1*) will leverage multiple permanent magnets in conjunction with magnetic polymer composites, exploiting their close-range interactions to create highly agile probes with variable stiffness properties. It is expected to result in magnetic probes optimized for clinical use and compatible with various clinical and pre-clinical magnetic actuation systems (*Figure 2*).

Future implementation of magnetic surgical systems towards treatment of CVDs holds much promise considering the wide interest and development in research institutions around the world. One of the primary topics of research today is related to the interdependency of actuation system and magneto-surgical tool, which has significant implications on the future applicability of the technology. Current trends include downsizing actuation systems (for example, robotic arms with magnetic end-effectors as shown in *Figure 2*), integration of actuation systems with medical imaging technology, and development of new tools with improved magneto-mechanical coupling to the actuation system. In the short-term, clinically adopted systems will likely remain focused on improving endovascular navigation and functionalization of wires and catheters.[9] Long-term, we may see possibilities with untethered magnetic agents, such as microrobots for localized drug delivery and targeted therapy, which decreases the need for stent implantation in delicate arteries.[10] In both scenarios, research developments on the actuating systems must keep up with variable requirements imposed by developments related to surgical tools. Consequently, hospitals may specialize in different types of magnetically assisted cardiovascular interventions depending on the instruments and actuation systems at hand.

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Declarations

Disclosure of Interest

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