Institution: University College London

Unit of Assessment: 15 (General Engineering)

a. Overview

This submission showcases UCL's unique biomedical engineering research capability and environment. UCL has excellence in biomedicine as well as engineering across all the core disciplines, and is thus exceptionally well placed to support outstanding biomedical engineering research from exploration of fundamental principles to clinical engagement. For RAE 2008 this activity was distributed across several submissions; subsequent strategic development at UCL and reorganisation of REF Units of Assessment permits us to make a unified submission reflecting all our biomedical engineering activity. With 55 Category A researchers (53.7 FTE) we are one of the largest concentrations of biomedical engineering research in Europe.

In 2012 UCL established a new Institute of Biomedical Engineering (IBME) that provides an integrative framework of strongly collaborative and mutually supportive academic departments and institutes engaged in medical technology research & development, and the twenty-five NHS Trusts and Hospitals that comprise the UCL Partners Academic Health Science Centre. It supports and promotes science, innovation and translational research in medical technologies: i.e. the non-pharmaceutical products used to diagnose, monitor, and treat human diseases and medical conditions. The cohort of Category A staff within the IBME submitted under this Unit are drawn from the following UCL departments/institutes (staff numbers in brackets):

- Department of Medical Physics & Bioengineering (16)
- Department of Mechanical Engineering, Biomechanical Engineering Group (13)
- Institute of Orthopaedics and Musculoskeletal Science (20)
- Department of General Surgery, National Medical Laser Centre (2)
- Department of General Surgery, Centre for Nanotechnology & Regenerative Medicine (1)
- Institute of Nuclear Medicine (2)
- Department of Internal Medicine, Applied Biomedical Engineering Group (1)

The first two are departments within the UCL Faculty of Engineering. The Department of Mechanical Engineering (MechE) is divided into three thematic groups, one of which is devoted to Biomechanical Engineering. The next five departments/institutes are all within the UCL Faculty of Medical Sciences, which is divided into several Divisions. UCL's Institute of Orthopaedics and Musculoskeletal Science (IOMS) is located within the Division of Surgery and Interventional Science, and is based on the site of the Royal National Orthopaedic Hospital (RNOH) in Stanmore. The same Division also contains the Research Department of General Surgery, which is home to the Centre for Nanotechnology & Regenerative Medicine (based at the Royal Free Hospital) and the National Medical Laser Centre (based at UCL Hospital). UCL's Institute of Nuclear Medicine (INM), which is the only academic department of nuclear medicine in the UK, is located within the Division of Medicine along with the Department of Internal Medicine, which is home to the Applied Biomedical Engineering Group.

b. Research strategy

a) **Relationship to institutional research strategy**

Biomedical Engineering has recently benefitted from considerable strategic investment by UCL, including creation of the IBME (and provision of coordinating staff), targeted appointments supported by the Faculties of Engineering and Medical Sciences, and investment in new facilities. This is in the context of a major expansion of UCL Engineering.

UCL has a longstanding strategic commitment towards nurturing interaction between different disciplines as a means of engendering innovation in research. Nowhere is this more pertinent at UCL than within its biomedical engineering community, which thrives because of the healthy culture of inter-disciplinarity. Researchers within this community readily recognize the necessity to transcend subject boundaries (particularly that between engineering and medicine), and this is evidenced by the overwhelming proportion of research projects involving co-investigators from

multiple disciplines, and the huge diversity in sources of research funding. For example, the UCL Faculty of Engineering regularly facilitates cross-disciplinary exchanges through innovative events such as "research speed dating", "bridging the gap sandpits", and Pecha Kucha events. UCL has further incentivised such exchanges by offering funding for pilot projects in health and wellbeing via its Crucible scheme, which also provides an online forum for sharing ideas and seeking collaborative partners. Wider collaboration with external organisations (such as companies and government institutions) has been supported at UCL through its Impact Awards, which provide half the cost of a PhD studentship, the remaining being matched by the organisational partner. The thematic emphasis of the UCL Research Strategy is embodied in four Grand Challenges, two of which ("Global Health" and "Human Wellbeing") are central to research conducted within this Unit, whose collective goal is to deliver technology that enhances the quality of healthcare. Institutionally, UCL's vision has been underpinned by very large investments in research at the interface between engineering and the biomedical sciences, including the creation of new centres of excellence (e.g. the London Centre for Nanotechnology and the Centre for Advanced Biomedical Imaging).

UCL has recently adopted a more cohesive approach toward biomedical engineering activity and research strategy via the creation of the IBME, launched in 2012. The institute represents an inter-connected community of biomedical scientists and engineers, medical physicists, and clinicians. While supporting research strategies within individual departments, the IBME was established to ensure such strategies are "joined up" and to fully exploit opportunities for cross-departmental collaboration and exchange of expertise. The IBME is set up to encourage the community towards greater translation of research outputs, and to serve as a valuable link between early-stage laboratory-based research and outcomes ripe for commercialisation. The future strategy for this Unit's research is heavily focussed towards enterprise and innovation.

b) **Progress against RAE 2008 strategic aims**

Prior to the establishment of the IBME in 2012, research within this Unit (and fulfilment of the UCL vision) has been largely driven by strategies devised by individual departments, and guided by research plans outlined in the RAE 2008. For example, four strategic objectives were specified for research activities within the Department of Medical Physics & Bioengineering (MPB) in the RAE 2008 submission. These, and the extent to which they have been achieved, are described below:

i) *To extend and strengthen research links between MPB and other UCL centres and departments*. This has been crucial to the department's recent successes; the department has undergone a radical culture change from being an appendage to the UCL Physics & Astronomy department (with which it was submitted in RAE 2008) to its current position at the centre of UCL's thriving biomedical engineering community, as exemplified by the IBME. The department has established highly productive research links with many departments and centres, most notably MechE, Computer Science, Electrical & Electronic Engineering, the Centre for Advanced Biomedical Imaging, the National Medical Laser Centre, the IOMS, the Institute of Nuclear Medicine, and the London Centre for Nanotechnology (LCN).

ii) *To promote a major expansion of research in photoacoustic imaging, especially applied to small animal and molecular imaging in collaboration with the new UCL Cancer Centre*. Since 2008, the photoacoustics group has generated £9.7M in funding, and has grown from 7 to 25 researchers. Landmark achievements during this period include: the first demonstration of backward-mode 3D photoacoustic scanner in 2008; the launch of the "k-wave" Matlab toolbox in 2009 (now the standard software for photoacoustic simulations, with over 2000 registered users in 60 countries); the first in-vivo 3D photoacoustic image of subcutaneous vasculature in human skin in 2009 (highlighted in *The Engineer* and *BioOptics World*); the first in-vivo demonstration of a combined OCT-photoacoustic tomography scanner for dermatological applications in 2011; the first in-vivo photoacoustic images of mouse embryos in 2012; the first photoacoustic images of a mouse model of human colorectal tumours and their response to anti-vascular therapy in 2012 (highlighted in *Laser Focus World*); and the first photoacoustic image of genetically-engineered tyrosinase expressing reporter gene in 2013. The department has created three additional laser laboratories to support growth in these activities.

iii) *To enhance the department's involvement in, and support of, x-ray phase contrast imaging*. This

involved creating a permanent post for the EPSRC Career Acceleration Fellowship-holder leading this activity, and reassigning departmental space to accommodate his expanding research team (now consisting of seven researchers). Since 2008, research income for x-ray phase contrast imaging has grown to a total value of over £5M, and the group has achieved a number of notable firsts: the first full-scale images in 2011(highlighted in *Nature* and *Scientific American*), the first demonstration (on cartilage tissue) of quantitative phase retrieval in 2012, and the first demonstration of mammography at an acceptable radiation dose in 2013.

iv) *To expand new developments in nanotechnology to healthcare applications*. Since 2008, the senior academic leading this activity has transferred from the LCN to MPB. During this period, the research group expanded from 5 to 25 researchers. Around £11.5M has been generated in R&D funding, and a further £8M in technology transfer funding and value generations (through spinouts Endomagnetics Ltd. and Resonant Circuits Ltd.). In 2010 Endomagnetics appointed a full-time CEO and obtained CE marking for its SentiMag product, making it available to surgeons and hospitals around Europe.

Overall, MPB has maintained a strong focus on clinical translation, with most research activity conducted in collaboration with hospital clinicians and/or industrial partners in the healthcare technology sector. It is now the largest self-contained academic medical physics department in the UK. The department has pursued a strategy of growth through developing new research areas by early-career staff, supported where possible by externally-funded fellowship awards. In alignment with the IBME strategy, MPB will continue to pursue medically-driven research through engagement with healthcare providers and the healthcare technology industry. It plans to maintain its internationally-leading research programmes in biomedical optics (including photoacoustics), radiation physics, implanted devices, magnetic resonance imaging, and electrical impedance imaging. Important priority areas for future development are as follows:

i) Proton therapy physics. UCL Hospitals NHS Trust, in partnership with UCL, has been awarded a £100M National Proton Therapy Centre, due to start clinical treatments in 2017. This will be a world-leading facility in a new area of cancer treatment using beams of high energy protons. This represents a wonderful opportunity for UCL scientists to take an international lead in the development of proton therapy research. The department of MPB has recently created a proton therapy research group, and are in the process of recruiting a chair in radiotherapy physics. In 2013 the department set up a Doctoral Training Programme in the physics of cancer therapy in order to train the next generation of researchers in this field.

ii) Interventional devices. Improvements in miniaturisation are enabling imaging and sensing devices to be placed at the ends of needles and catheters inserted within the body. The devices enable more accurate and safer placement, and optimal delivery of drugs and extraction of biopsy samples. During the past two years the MPB department has established a new interventional devices group as a priority area for future growth, with external funding already exceeding £1.5M. Three new laboratories have been created to support this work.

iii) Ultrasound. MPB has created a new biomedical ultrasound group, bringing together researchers involved in acoustic, photoacoustic, and acousto-optical imaging, and ultrasound-guided interventions. This is being driven by three early career researchers who have each recently been awarded permanent academic posts in MPB following completion of externally-funded fellowships. A suite of six new laboratories have recently been strategically assigned to the department to support the growth of its ultrasound research. The new group is being broadened to encompass ultrasound research in other UCL departments (e.g. MechE).

iv) Contrast agents and biomarkers. A variety of exogenous contrast agents already exist or are being proposed for most medical imaging methods, and it is inevitable that research activity in this area will grow significantly. MPB researchers are exploring microbubbles and nanoparticles as contrast agents for ultrasound, MRI, and phase-contrast x-ray imaging, and molecular biomarkers for optical and photoacoustic imaging. This work is being pursued in partnership with groups outside the department, especially researchers in the LCN. Imaging research in the department is supported by a well-established Doctoral Training Programme in Medical & Biomedical Imaging, which attracts 5-10 students per year.

The Department of MechE and IOMS were submitted together in the RAE 2008 under the

Mechanical Engineering unit of assessment. They shared four strategic objectives for the following five years. Progress against each objective is summarised below:

i) *To support early career researchers (40% of submitted staff) to become world leaders in their fields*. Those researchers in MechE are now well established, having completed periods of probation. They have set up their own groups and lead activities covering a wide range of cutting-edge research, including cardiovascular engineering, biophysics, and medical devices. A five-year fellow at IOMS reported in RAE 2008 has subsequently obtained a UCL lectureship. Three IOMS staff reported as lecturers in RAE 2008 have since been promoted and have secured EPSRC, BBSRC, and MRC project grants. IOMS has two current staff on fellowships (MRC and BBSRC), one of whom has already secured a permanent post at UCL.

ii) *To enhance world-class research facilities through internal and external funding and industrial partnerships*. The department of MechE has developed several funded research programmes with strong translational value, involving internal and external partners. Examples are: a) a consortium with the Institute of Cancer Research UK, Oxford University, the National Physical Laboratories, and UCL's Centre for Medical Image Computing, which was awarded a £5M EPSRC grant concerned with high-intensity focused ultrasound for the ablation of cancerous tumours; b) joint research with the UCL Department of Surgery to win a £1M Wellcome Trust Translation Award for the development of a novel artificial valve for transcatheter implantation; c) new translational collaborations with clinical units at Moorfields (ptosis) and Whittington Hospitals (urinary tract infections) supported by a combination of EPSRC (£187K) and hospital trust (£49K) funding.

IOMS research is strongly driven by industrial collaboration. For example, Stanmore Implants Worldwide, a company spun out of IOMS, is now a highly successful orthopaedic implant manufacturer, and most of its IP and expertise was developed at IOMS. The company provides around £150K of research support per year, and collaboration has enabled IOMS to obtain a £2.1M Wellcome Trust grant. Meanwhile a collaboration worth £3.8M with Johnson & Johnson has enabled a new implant retrieval laboratory to be established at IOMS, associated with failed hip replacements. An initiative with a charitable organisation has enabled the refurbish-ment of a tissue culture facility and the establishment of a new microbiological laboratory in IOMS. EPSRC in collaboration with the Rutherford Appleton Laboratory at Harwell has funded the development of a new lab equipped for Raman spectroscopy of musculoskeletal tissues. This facility supports an on-going clinical trial on bone quality in patients. Finally, industrial collaboration and research council funding enables IOMS to maintain a unique *in vivo* facility based at the Royal Veterinary College, devoted to musculoskeletal research. This allows world-class research on animal models of musculoskeletal disease, the effects of biomaterials and medical devices on repair, and regeneration/remodelling of the musculoskeletal system.

iii) *To increase engagement in interdisciplinary research with life and clinical sciences*. This has been achieved by fostering many funded collaborations. MechE is engaged in joint projects with a) UCL Heart Hospital and University of Manchester Computer Science & Biology Departments; b) Moorfields Hospital and Cambridge Centre for Medical Materials; c) King's College London and Orthopaedic Research UK; d) National Institute of Health, USA, Southampton University (Dept. Medicine), Columbia University (Dept. Medicine), UCLH and Great Ormond Street Hospital. Many research collaborations exist across the UCL Division of Surgery between IOMS, the Centre for Nanotechnology & Regenerative Medicine, and the Department of General Surgery. Collaboration between IOMS and the National Medical Laser Centre has enabled monitoring of oxygen levels *in vitro* in long-term tissue engineered and organ constructs. Additionally IOMS runs small animal models at the Institute for Medical Research at Northwick Park Hospital. A charity-funded laboratory has been jointly set up by IOMS and the Eastman Dental Institute. On a wider scale, IOMS collaborates with clinical academics working at the UCL Institute of Ophthalmology and Moorfields Eye Hospital.

iv) *To position the biomedical engineering activities at IOMS across the faculties of medicine and engineering*. IOMS is now fully integrated within the IBME, with the Director of IOMS serving as the IBME's Deputy Director. Many collaborations exist across the centres within this Unit, including new highly productive partnerships between medicine and engineering.

Having established biomedical engineering as one of three major research themes within MechE in

2005, the department has sought a strategic expansion in this area during the assessment period through recruitment of two professors, including an established Chair of Biomaterials, and seven lecturers. The department's Biomechanical Research Group, which meets several times a year to discuss and implement research strategies, operates under four research themes. Two of these - Biomaterials & Therapeutics and Ultrasonics are long-standing and world-leading. Since RAE 2008 they have grown significantly through a large portfolio of research council, charity and industrial grants. The additional two themes - Medical Devices and Cardiovascular Engineering were more recently established following a strategic decision to invest in these areas through recruitment of early-career academic staff.

Over the next five years, biomedical engineering research in MechE will focus on expanding and strengthening the current core of activity. The cardiovascular engineering research has recently been augmented through a new lecturer appointment, who has already established research projects with the Royal Brompton and Harefield Hospitals and the Qatar Cardiovascular Research Centre. The department is also growing a new research area, prompted by another academic appointment, of mathematical modelling of biomedical engineering concepts, such as tissue engineering (in collaboration with IOMS).

Research activity at IOMS is clinically-driven, and heavily focused on translational research in orthopaedics and rehabilitation engineering. Their mission is "to be a world-leading centre for innovative translational research in the restoration of life-long pain-free functional mobility and high quality independent living." Research priorities at IOMS during the next five years are:

i) Innovative implant design. The Institute's international lead in biomedical engineering and innovative implant design will be maintained and extended through collaboration with academic, clinical and commercial partners.

ii) Cell and tissue engineering related therapy. Research will focus on translating cell therapy and tissue engineering activity into clinical use and commercial development. This will involve conducting early phase clinical trials. IOMS currently runs two clinical cell therapy trials funded by MRC and the UK Stem Cell Foundation.

iii) Disability Science and improving quality of life and independent living. IOMS will establish a Centre of Disability Science with translational research in assistive technology. This will be achieved through partnerships with Aspire (a charitable organisation in spinal disability) and the UCL Faculty of Engineering.

iv) High burden musculoskeletal disease (e.g. osteoarthritis, osteoporosis and fragility fractures). Clinical research will be developed in the area of high burden musculoskeletal disease, based on the Institute's national leadership of important databases such as the National Joint Registry and the National Hip Fracture Database.

While groups, departments and institutes will continue to pursue specific research themes appropriate to their expertise, overall research strategy will be guided throughout by the collective wisdom and resources of the IBME, exemplified by its Executive Team (Director, and Deputy and Associate Directors) and its Academic, Clinical & Enterprise Board, representing UCL's leaders in biomedical engineering research and enterprise, and other key stakeholders.

c. People, including:

i. Staffing strategy and staff development

The institutional staffing strategy for this Unit has been one of significant growth through sustained investment, as evidenced by the recent establishment of the IBME. This has been realised through recruitment of early-career and senior individuals in selected research areas, either to underpin existing strengths or to develop new lines in emerging areas of national importance. Staffing strategy has been heavily focussed on mentoring postdoctoral staff towards competitive five-year fellowships. For example, MPB has three reported staff currently supported on fellowships (EPSRC Career Acceleration, Welcome Trust Career Development, and EU Starting Grant), and has three additional reported staff who completed fellowships (all EPSRC) during the period of assessment. The department has an excellent track record of securing permanent posts for fellows at the end of fellowships: all six of its former fellows are now among its HEFCE-funded academic staff, three of

whom are professors. IOMS staff reported within this Unit also includes three with research fellowships (MRC, BBSRC and the Royal College of Surgeons), each of whom has secured or is very likely to secure a permanent post at IOMS. The London Deanery also funds two academic clinical fellowships at IOMS.

The Biomechanical Research Group in the department of MechE was created in 2005 through recruitment of external staff, including professorial appointments from Queen Mary University and Kings College London, and new lecturers from Cambridge, Oxford, and Imperial College. An additional lecturer appointment was recruited from a leading European cardiovascular and medical devices company. The department of MPB has also made strategic appointments in areas of interventional devices (lecturer), MRI (lecturer), and ultrasound therapy (reader), and is now appointing a chair in proton therapy. Both lecturers were appointed from positions held overseas. IOMS has recently appointed two academic clinical lectureships under the Walport Scheme, which promotes a new integrated clinical academic career pathway.

New academic staff at UCL are subject to a period of probation. All probationary academic staff are also assigned a mentor (normally a senior member of the same research group, and often the head of group), who meets with the individual on a regular basis and provides guidance on all aspects of their career development. For example, all probationary lecturers in the Department of MechE at the time of RAE2008 (two out of six are females) have subsequently completed their probationary periods (and two have been promoted).

All UCL staff are subject to annual appraisal, which is used as a mechanism for considering a case for promotion and identifying training requirements. All postdoctoral research staff within the unit receive regular mentoring, typically by a senior academic within the same group. However, the department of MPB has recently implemented a scheme which provides all postdoctoral staff with a mentor outside of the staff member's research group, who meets with them at least twice per year. The scheme is coordinated by a committee of postdoctoral staff volunteers, and ensures that early-career researchers are kept informed of fellowship opportunities as well as assisted with general career development. All postdoctoral staff within UCL's biomedical engineering community are also invited to attend monthly UCL meetings which highlight specific research council and other fellowship opportunities.

While females represent only 28% of the reported staff in this Unit, this proportion is steadily growing and is well above the average for UK engineering departments. The Division of Surgery submission to this Unit includes 10 new academic appointments and fellows, of which 6 are female. The MPB department has been highly proactive in promoting careers in medical physics to women, and was awarded an Athena SWAN Bronze award in 2013. Nine out of a total of 17 MPB research staff appointed in 2011/12 were female.

ii. Research students

During the period of assessment there have been considerable changes in the structure and administration of graduate research degrees at UCL. There has been a drive towards four-year instead of three-year degrees, and an emphasis on doctoral training programmes (DTPs). An increasing number of students now elect to follow a 4-year DTP, starting with a one-year MRes. The MRes typically involves taught modules, one or more laboratory projects (not necessarily linked to the PhD project), and transferable skills elements, such as a journal club.

Research students are recruited through many different routes, and approaches vary considerably between different departments/institutes, depending on the types of funding for studentships. MPB has students recruited via competitive interviews to join one of several DTPs. For example, the Medical & Biomedical Imaging DTP runs an effective recruitment campaign which attracts many dozens of applicants for its handful of funded studentships available each year. The applications are carefully reviewed by a panel and a shortlist is created. Studentships are also funded via research council or charity project grants, or via industrial sponsorship. UCL also enables recruitment of excellent students via competitive Graduate School Scholarships, and via the "Impact Studentships" scheme which provides funding for PhD studentships to match that from a non-research-council source. An increasing fraction of research students in MPB and MechE are self-funded overseas students; some respond to specific advertisements, while others are recruited following a direct approach to potential supervisors. All applicants are interviewed (in person or via

phone/skype) by at least two members of staff. Since RAE 2008, a total of 123 UCL students have competed PhD degrees in research areas under this unit of assessment. A further 91 are currently registered on a research degree, of which 48 are research council-funded.

All UCL students engaged on a PhD degree are initially registered for an MPhil degree, and are required to maintain an online log book which entails them following a strict timetable of progress monitoring and assessment. This involves providing a progress report and updated research plan every 3 months during the first year, and every 6 months thereafter. Each report and plan is reviewed by first and second supervisors. In addition, students are required to provide at least one formal oral presentation to the department and one poster presentation. All students are expected to undergo an assessment process for transferring registration from MPhil to PhD during the first half of their second year. This involves writing an extensive report and then defending it during oral examination. The exam is intended to identify any students failing to meet the necessary criteria for gaining a PhD, or those who are in the process of deciding that undertaking a PhD is not appropriate for them. Should examiners have concerns about the project, the supervisors are advised (by the examiners and the Graduate Tutor) on how the project should be modified. Any student who fails to transfer is allowed a second attempt within 6 months. All UCL research students are expected to take full advantage of the training opportunities available at UCL, including the Graduate School Skills Development Programme, for the equivalent of two weeks per year. A large number of training programmes run at UCL, designed to expand generic research skills and personal transferable skills.

In 2011, the department of MPB introduced a compulsory taught module for all first-year PhD students whose purpose is to train students in effective scientific writing, oral presentation, searching scientific literature, and other basic communications skills. All MechE research students are expected to attend short courses on research planning, management & execution offered by the UCL Graduate School, and via their online logbook present this training to the MechE PhD Tutor before transfer is approved. PhD students at IOMS are required to take part in a weekly journal club, with individuals expected to lead two meetings per term.

UCL students are also encouraged to take part in a Yale UCL Collaborative Student Exchange Programme, which gives them the opportunity to undertake a period of research at Yale (of up to 3 months) as part of their doctorate under the supervision of an identified Yale Supervisor.

d. Income, infrastructure and facilities

The research activities within this Unit benefit from their location in a city with one of the world's largest and most active communities of world-leading hospitals and biomedical research facilities, which engenders a culture of clinical engagement and translation of technologies. The staff submitted within this Unit are strongly integrated within this community, occupying offices and laboratories throughout and beyond UCL's Bloomsbury campus.

The department of MPB is primarily situated within three floors of the Malet Place Engineering Building. The department moved into the new building in 2004, which contains a large suite of laboratories purpose built for research using x-ray and radioactive sources, and lasers. It is also equipped with a Clean Room for development of implantable devices, two laboratories licensed for animal measurements, and a clinical procedures room for ethically-approved measurements involving human volunteers. The building also houses several electronics and mechanical laboratories for assembly of instrumentation. The department has one full-time technician, although staff are also able to use the services of larger mechanical and electrical workshops in adjacent departments. MPB research staff also occupy laboratories and offices in nearby medical school facilities. Since RAE 2008, growth in several research priority areas has resulted in the reassignment of several rooms and laboratories, and a major refurbishment programme to ensure the department makes the optimum use of available space. This creation of new spaces for research has been facilitated through institutional support as well as through substantially increased research income. The same period has also seen a dramatic rise in the intake of research students (from 41 in 2008/09 to 83 in 2012/13).

Strategies and priorities for research within the department of MPB are defined by the Departmental Research Committee, which meets monthly. One of its primary functions is to ensure

the department's research community is aware of (and therefore exploits where appropriate) new funding opportunities. This includes identifying and encouraging suitable candidates for fellowship calls.

The Biomechanical engineering group laboratory infrastructure within the department of MechE is relatively new following refurbishment during 2007-2010, funded by a Wolfson Foundation & Royal Society Grant. This included the creation of four new laboratories, supported by eight technical staff. However, with the rapid growth of research activity, some research teams are already requiring the allocation of additional space, such as the Biomaterials Processing Laboratory which includes more than a dozen research students. MechE departmental research strategy is discussed at the Departmental Research Committee (DRC) every 3-months, and in greater detail at the biomechanical engineering group meetings which precede each DRC. Such meetings are used to plan and coordinate large grant applications, and interdisciplinary collaboration is discussed and organised.

In 2012 the UCL Faculty of Engineering launched its Institute of Making, led by its Director Prof. Mark Miodownik (submitted with this Unit). The Institute's mission is to "provide all makers with a creative home in which to innovate, contemplate and understand all aspects of materials and promote, inspire and celebrate their relationship to making". The Institute is closely allied to the departments of MechE and MPB, and its facilities significantly impact biomedical engineering research, especially the support and training of research students.

IOMS, located on the site of the RNOH, is divided into four research centres located within two buildings. The largest is the John Scales Centre for Biomedical Engineering, which employs 16 staff. The others are the Centre for Academic Clinical Orthopaedics, the Centre for Tissue Regeneration Science, and the Centre for Disability Science. The heads of the four centres report to the IOMS executive committee, which meets once per month. Once every quarter an academic board is held which all academic staff are required to attend. These two meetings highlight new funding opportunities and encourage appropriate responses. Research themed meetings are also held to encourage cross centre collaboration and identify suitable grant schemes. These themes also involve hospital consultants who identify clinical problems, which can then be translated into grant proposals where appropriate. Since 2008 research at IOMS has diversified with new labs created for Raman spectroscopy, microbiology, metrology and implant retrieval. Redevelopment at RNOH in 2014 will include refurbishment of IOMS and relocation of the John Scales Centre for Biomedical Engineering at a cost of £4-6M.

Since 2008, the breakdown of *spent* external funding obtained for research within this Unit is estimated to be as follows: £14.0M from Research Council grants; £4.3M from UK Charity funding; £3.4M from Industrial support; £3.4M from UK government (e.g. Home Office, TSB etc.); £2.3M from EU government bodies; £0.8M from other sources. In-kind support during this period, mostly in the form of project partners on translational grants, is estimated to exceed £14M.

e. Collaboration or contribution to the discipline or research base

a) **Collaboration**

The strategy underpinning all research collaborations within this Unit is of maximising clinical impact through an interdisciplinary alliance between the developer (scientist and engineer), the end-user (the doctor and the patient) and/or the commercial partner. UCL actively facilitates and incentivises cross-disciplinary exchanges between academics through networking events and prioritised funding schemes (see *Research Strategy* above), and such collaboration is fundamental to biomedical engineering activity at UCL. Research teams within a single department are often themselves multidisciplinary, as exemplified by the Biomedical Optics Research Laboratory within the department of MPB, whose staff include physicists, engineers, mathematicians, life scientists, and computer scientists. Another example in the same department is the Electrical Impedance Tomography group, which is led by a consultant neurophysiologist and includes physicists, mathematicians, computer scientists, and other clinicians. The department of MPB is also home to the UCL Centre for Medical Image Computing (CMIC), a group of around sixty physicists and computer scientists, whose Category A staff are being returned with the REF Unit of Assessment 11 (Computer Science). Imaging underpins much of the work performed within the IBME, and

many of the researchers within this Unit have collaborations with CMIC, who themselves collaborate extensively with many hospital departments and industrial partners.

All reported staff in this Unit have interdisciplinary academic collaborations which involve other UCL departments and other UK institutions. In most cases partnerships serve to provide complementary expertise in areas such as medicine, theoretical physics, mathematics, computer science, biology, electronic and chemical engineering. An exemplar of a successful UCL-led national collaboration is the £5M EPSRC-funded Consortium led by Prof. Nader Saffari in the area of high-intensity focussed ultrasound for the ablation of cancerous tumours, involving scientists and engineers with CMIC, the Institute of Cancer Research, Oxford University, and the National Physical Laboratories. There are also many examples of participation in extensive international consortia, often with UCL staff involved in leadership roles. Prof. Robert Brown has established and maintains two interdisciplinary research networks concerned with tissue engineering: an EU-funded consortium on Nano-biomedicine, and a BBSRC-funded Biotech network supporting collaborations between four UK and four Chinese universities.

Central to much research activity within this unit of assessment is the alliance between the basic scientist and the hospital-based clinician. Most reported staff have clinical collaborators, many based within the UCL Hospitals NHS Trust, and others within a very broad range of hospitals throughout the UK and beyond. For example, Dr. Adrien Desjardins has established EU and EPSRC funded projects with consultants at UCLH, an electrophysiologist at the London Heart Hospital, and a research team at Harvard Medical School. Prof. Jem Hebden leads projects in partnership with neonatologists at Addenbrooke's Hospital Cambridge supported by over £1M of joint funding from EPSRC and other sources. Prof. Mohan Edirisinghe has EPSRC-funded collaborations with ophthalmology consultants at Moorfields Hospital and with urologists at Whittington Hospital. Prof. Alister Hart, a consultant orthopaedic surgeon, has established many productive collaborations with scientists and clinicians in the UK and USA focusing on the introduction of new orthopaedic implants into clinical practice. Prof. Clare Elwell leads a project funded by the Bill & Melinda Gates Foundation, with research collaborators in Oxford, Gambia, and India.

Over 90 percent of reported staff are engaged in industrial collaborations, primarily as a route to translation into marketable products. Engagement between UCL academics and industry is supported through the services of three internal organisations. First, UCL Advances offers training, network and business support for staff, students, and external entrepreneurs to facilitate the launch of new enterprises. Second, UCL Business is a technology transfer company which supports and commercialises research and innovations arising at UCL. Third, UCL Consultants Ltd. supports academics undertaking consultancy.

As reported above, the spinout company Endomagnetics Ltd, founded by Prof. Quentin Pankhurst, has a product which is now sold to European hospitals, protected by patents filed by UCL Business. Prof. Paul Beard's ultrasonic fibre-optic hydrophone, patented with assistance of UCL Business, is manufactured by Precision Acoustics Ltd, with sales in at least eight countries. Prof. Gordon Blunn, working with a variety of industrial collaborators including Johnson & Johnson, Smith & Nephew, Baxter, Stanmore Implants, and Biomet has overseen the introduction of several products into clinical practice, such as a non-invasive growing prosthesis which is fully-patented and FDA approved, and a license to manufacture the device has been granted to Stanmore Implants. Prof. Allen Goodship's development of a stem cell therapy for tendon injury has led to a commercial treatment (marketed by VetCell) for horses and a clinical trial on humans. Prof. Mohan Edirisinghe's UCL spinout company AtoCap Ltd., set up after winning the 2010 Venture Prize, has developed patented drug delivery technology being trialled at Whittington Hospital to treat urinary tract infections.

Prof. Robert Speller's extension of new x-ray technology from healthcare into security applications has resulted in highly productive (and well-funded) collaborations with a broad range of UK (3DXray Ltd., Rapiscan, AWE, IATA) and international (Nikon) organisations, and with three UK Government departments (CAST-Centre for Applied Science & Technology, UK Border Agency, DSTL-Defence Science & Technology Laboratory). These serve to define user requirements, provide facilities of in-field testing of prototypes, and provide contact with end users (e.g. police

forces, first responders, and customs officers).

Institutional support via the Office of the Vice Provost for Research is also provided to assist staff in exploiting specific calls for funding to facilitate translation. For example, Dr. Richard Day obtained a Wellcome Trust Translation award and an MRC Discipline Hopping Award to support translation of a biomedical device from the laboratory to a clinical product. Dr. Richard Day was further assistant by UCL Consultants to negotiate consultancy agreements with several pharmaceutical companies. The development of artificial heart valves by Dr. Gaetano Burriesci also received a (£1.2M) Welcome Trust Translation award, in addition to a contribution from commercial partner Johnson & Johnson (£30K) and an EPSRC case award in collaboration with TWI (£90K).

In addition to their academic and industrial collaborations, some reported staff also have close working relationships with national and international laboratories and facilities. For example, Dr. Alessandro Olivo's development of phase-contrast x-ray imaging involves collaboration with three national synchrotron facilities, in the UK (Diamond), France (ESRF), and Italy (ELETTRA). This is in addition to more than ten industrial partners, including Nikon, Canon, and QinetiQ. Meanwhile, Prof. Alan Cottenden has collaborations with more than a dozen companies involved in incontinence products, including several of the leading multinationals. He collaborates with virtually all the leading international scientists in his field, and has thus been able to influence and inform research strategy, influence clinical practice, modify public/patient attitudes and behaviour, and define new international standards.

As part of the establishment of UCL's IBME in 2011, a Yale-UCL MedTech initiative was launched to encourage new joint translational projects. The IBME also runs a MedTech Voucher Scheme, in collaboration with Capital Enterprise Ltd. This is government funded to encourage local medical technology SMEs to collaborate with UCL academics.

Finally, staff are also involved various training networks. This is exemplified by Dr. Vanessa Diaz, who leads a multi-centre Marie Curie network (cardiovascular engineering and medical devices) involving eight academic institutions around Europe.

b) **Contributions**

The list below highlight some of the contributions made by reported staff to their research discipline, and how such contributions have been recognised by the community at large.

i) Society Fellowships: ACPSEM (Hutton), British Orthopaedic Association (Hart), Higher Education Academy (Day, Hanson), Institute of Materials, Minerals & Mining (Huang), Institute of Physics (Hebden, Holder), IPEM (McCarthy), Royal College of Physicians (Holder), Royal Institution (Miodownik), Royal Society of Chemistry (MacRobert), Society of Biology (Edirisinghe).

ii) Society Boards and Committees: IMechE Engineering in Medicine & Health Division (Cottenden), IoP Physical Acoustics Group (Cox), ISMRM Study Group on Susceptibility Weighted Imaging (Shmueli), UK Tissue & Cell Engineering Society (Mudera), President of British Orthopaedic Research Society (Goodship), International Society for Fracture Repair (Goodship), Secretary of British Orthopaedic Research Society (Blunn), Chair of IPEM Rehabilitation & Biomechanics Special Interest Group (McCarthy), Secretary of Association Research Circulation Osseous (McCarthy), President of Tissue & Cell Engineering Society (Brown), Council of Head & Neck Optical Diagnostics Society (MacRobert), Honorary Secretary of IoP Physical Acoustics Group (Saffari), Board of Institute of Materials, Minerals & Mining (Huang), Computational Materials Science Committee of Minerals, Metals and Materials Society (Miodownik), Chair of International EIT Steering Committee (Holder), Chair of Committee of International Federation of Medical & Biological Engineering (Holder), Simon Foundation USA (Cottenden), Inspire Charity (Donaldson), Trustee of UK Bladder & Bowel Foundation (Cottenden), Thomas Young Centre (Miodownik), BSI & ISO Committees on Incontinence Products (Cottenden), International Photothermal & Photoacoustic Association Prize Committee (Beard).

iii) Funding agency panels: EPSRC (Hart), Action Medical Research (Gibson); STFC Advisory Panel (Speller), RCUK Global Uncertainties Review Panel (Speller), UK Olympic Security Review Panel (Speller), NASA Crew health grants panel (Goodship), ARUK (Hart, Goodship), ARUK Advisory Board on Metal-on-metal hip replacements (Blunn), Royal Society Newton International

Fellowship Committee (Beard), British Orthopaedic Association (Hart), Orthopaedic Research UK (Hart), Scientific Advisory Board for National Science Foundation Ireland (Brown), University of Southampton Nuffield Council on Bioethics (Brown), Andalucian Initiative on Advance Therapies (Brown), DoH expert panel member (MacRobert), Wellcome Trust/MIT fellowship panel (MacRobert), Chair of AMR Medical Engineering panel (Holder).

iv) Funding agency peer-review: All reported staff contribute regularly to peer-review for UK research funding agencies (EPSRC, BBSRC, MRC, STFC, NIHR), UK charities (Wellcome Trust, Action Medical Research, etc.), and other funding bodies throughout Europe & beyond.

v) Journal Editorial Board: Journal of Biomedical Optics (Beard); Muscles, Ligaments & Tendons Journal (Birch); International Journal of Biomaterials (Blunn, Edirisinghe); Journal of Engineering in Medicine (Cottenden, Ventikos); Current Stem Cell Research & Therapy (Day); Open Biomedical Engineering Journal (Day); Journal of Tissue Engineering (Day, Mudera); Journal of Bubble Science, Engineering & Technology (Edirisinghe); Journal of the Royal Society Interface (Edirisinghe); Hard Tissue (Goodship, Seifalian); MBC Medical Physics (Hebden); Physics in Medicine & Biology (Hebden); Advances in Applied Ceramics (Huang); Biomatter (Jayasinghe); Macromolecular Bioscience (Jayasinghe); Artificial Cells, Nanomedicine & Biotechnology (Jayasinghe); Materials Today (Jayasinghe); Organogenesis (Jayasinghe); Biotechnology Journal (Jayasinghe); BioProcessing Journal (Jayasinghe); Interdisciplinary Science Reviews (Miodownik); Ultrasound (Saffari); International Journal of Numerical Methods in Biomedical Engineering (Ventikos); Acta Mechanica (Ventikos); Computational Bioengineering (Ventikos); Tissue & Cell Engineering Society Newsletter (Mudera).

vi) PhD Examiners: Reported staff frequently examine PhD students (often several times per year) at universities throughout the UK and many other academic institutions around the world.

vii) Keynote and invited speakers: Staff accept many invitations to give keynote and invited talks at leading international meetings in their research field. Highlights include the following keynote talks: UKRC 2013 (Speller); Medical Bionics 2011 (Donaldson); Bioengineering 2011 (Olivo); American Chemical Society 2009 (Edirisinghe), Materials Research Society 2010-2112 (Edirisinghe), MediTech 2011 (Diaz), International Conference on Self-healing Materials 2011 (Miodownik), Material Science & Technology 2008 (Jayasinghe).

viii) Awards: UCL Business Award 2010 (Pankhurst), European Innovation Board Academic Enterprise Award 2011 (Pankhurst), Royal Society of Medicine Orthopaedics President's Prize 2012 (Coathup), Royal Society Brian Mercer Innovation Feasibility Award 2009 and 2013 (Edirisinghe), Institute of Materials, Minerals & Mining Kroll Medal and Prize 2009 (Edirisinghe), Royal Academy of Engineering Rooke Medal (Miodownik), Worshipful Company of Armourers and Brasiers Venture Prize 2010 (Edirisinghe), UK Biomaterials Society Presidents Prize 2012 (Edirisinghe), UCL Consultant of the Year 2012 (Diaz), IADR/GSK Innovation in Oral Care Award 2010 (Huang), UK Business Innovation Award from UK Trade and Investment in Life Sciences and Healthcare 2009 (Seifalian), Medical Futures Innovation Award 2008 (Seifalian et al.), IMMM Sir George Beilby FRS Memorial Medal and Prize 2010 (Jayasinghe), Marian Smoluchowski International Award and Prize 2009 (Jayasinghe), IEEE Marie Sklodowska-Curie Award 2014 (Hutton).

ix) Conference chair: OSA Biomed Conference 2010 (Beard), INM Seminars (Hutton), IMechE "Incontinence: the Engineering Challenge" (Cottenden), Simon Foundation "Innovating for Continence" (Cottenden), Functional NIRS meeting 2012 (Elwell), British Orthopaedic Research Society 2012 (Coathup), Society for Fracture Repair 2010 (Goodship), Anglo-French Physical Acoustics Conferences 2000-2013 (Saffari).

x) Other significant contributions: Invited expert at IAEA International Workshops (Hutton). Scientific Advisory Board of RMS Innovations UK Ltd. (Goodship). RCUK Public Engagement Strategic Advisory Team (Miodownik). Royal Institution Christmas Lectures 2010 (Miodownik).