Chapter 1
Introduction

Lasers constitute a versatile tool in the treatment of diverse pathologies affecting delicate and vital human organs. Transoral laser microsurgery (TLM) is one important field of application. This is a suite of minimally invasive endoscopic techniques for the excision of minuscule laryngeal abnormalities [1, 2]. In these procedures, lasers are utilized for a variety of tasks, including precise tissue cutting, ablation and coagulation. The advantage over traditional cold instrument surgery is manifold: the combination of high power and minute beam focusing (down to a few hundreds microns in diameter) allows for the creation of small, clean incisions through tissues [1]. Lasers present the unique advantage of being able to cut and coagulate tissues at the same time, thus offering an enhanced control of bleeding [1, 2]. Laser cutting facilitates the cicatrizazion of tissues, resulting in less post-operative complications and shorter patient recovery time [2, 3]. Additional benefits of laser microsurgery in the larynx over other treatment modalities include smaller cost-per-procedure [4] and lower postoperative morbidity [1, 3].

Despite these many advantages, the use of the laser as surgical tool is not straightforward. To qualify for TLM, clinicians are required to undertake specialized training, aimed at developing a safe and effective laser cutting technique [2, 5]. In the surgical equipment available today, laser control consists of two parts:

- **Control of Laser Positioning**, which is required to delineate and execute the desired incision lines on tissues. In TLM, the laser position is controlled manually through a mechanical device called laser micromanipulator [6]. Because of the minuscule size of the organs involved, these interventions are carried out under microscope magnification. The micromanipulator is an effective control interface, yet it is difficult to master, especially because it breaks the hand-eye coordination of the operator [7].

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- **Control of the Laser Parameters**, these determine the characteristics of the resulting incision, i.e. depth, width and thermal effects on surrounding tissues. Modern laser systems such as the Lumenis Ultrapulse® or the Deka SmartXide^2 ENT present diverse parameters—including output power, spot size, pulse frequency and duration, exposure time. In the course of an intervention, these parameters are adjusted depending on the operative task at hand. For each application, no fixed set of parameters exists: clinicians may use different settings, depending on their skills, experience and preferred technique [1].

Evidently, laser microsurgeries require clinicians to possess a strong dexterity in the use of the laser for the management of soft tissues. The limitations mentioned above have recently stimulated new research and technological developments in this area: numerous works have explored the creation of computer/robot-assisted laser microsurgery systems [6–14], aimed to allow clinicians to control the laser motion through a digital computer and a robotic device. Support is provided for motion scaling, as well as for the automatic execution of pre-planned motion patterns, that enhance the precision and safety of laser microsurgery.

While recent developments have facilitated precise laser motions, the automatic control of laser incisions has not been realized until now, and remains largely unexplored. It is not evident how to regulate the laser operational parameters in order to achieve high quality incisions: this would require modeling the physical interactions that occur between laser light and tissue, which are inherently complex and not straightforward to describe [15, 16]. The control of laser incisions is performed manually by clinicians, who need to complete extensive practice to learn how laser parameters influence the laser cutting process. Learning the association between the manipulation of laser parameters and the corresponding effects on tissues is not straightforward, and is regarded as an essential component of a laser surgeon's skills set [2, 4, 5, 17]. Based on these challenges, the subject of this thesis is to lay out the groundwork for the monitoring and control of laser incisions during microsurgeries.

Laser incision of soft tissues is understood as an energy-based, thermal process: the energy associated with the laser beam is absorbed by the tissue under the form of heat, producing a local rise of temperature. Continuous temperature increase eventually breaks molecular bonds and results in the ejection of hot plume. This process is commonly referred to as *thermal laser ablation* and has been extensively studied in the past [15, 16], but has never been modeled for monitoring or control purposes. In this thesis, we build models capable of describing the development of laser incisions in soft tissues, given the same inputs used by the clinicians, i.e. the laser operational parameters.

Recent years have seen a growing interest in the use of artificial cognitive systems to monitor and control complex processes, that would be difficult to manage using classic control methods [18]. In the scope of this doctoral dissertation, we view artificial cognition as the framework of choice to model specific laser-induced effects on tissues, and use these models to endow surgical laser systems with the capacity to both monitor and the control such effects.

1.1 Motivations

This section presents an example that provides a qualitative description of the problems that motivate the research described in this dissertation. Figure 1.1 shows a magnified view of the human vocal folds, on which a tumor is highlighted. This is a Squamous Cell Carcinoma (SCC) [19], a common type of laryngeal cancer whose occurrence is primarily related to smoke and alcohol consumption [20]. SCC originates from the cells that constitute the superficial layers of the epithelium and may spread to contiguous structures [21], potentially impairing phonatory abilities. In addition to this, laryngeal SCC is a life-threatening disease: it is estimated that nearly 20 000 Europeans died of laryngeal cancer in 2012 [22].

When treating malignancies of the vocal folds, it is important not just to eradicate the tumor, but also to preserve as much organ functionality as possible. In practice, this translates to the use of surgical strategies aimed to minimize the extent of the dissection. Given the small size of the vocal folds, these interventions require greater precision: even 1 m of additionally resected tissue can make the difference between a successful resection and permanent vocal impairment [23, 24]. In this respect, the ability to control the depth of laser incisions is of paramount importance. This is influenced not just by the parameters that characterize the laser irradiation—such as laser power and exposure time—but also by the type and molecular composition of tissue, which is inherently inhomogeneous [25]. The laser incision depth decided *a priori* might not correspond to the actual one, therefore this must be tracked to ensure appropriate results. The contactless cutting method of the laser prevents clinicians from using their delicate sense of touch to discern the actual depth of incision, thus visual inspection is the only tool available to interpret the laser penetration depth.

Another factor of risk for the vocal function is represented by the onset of collateral laser-induced effects. Laser cutting of soft tissues is a thermal process, whose consequences might include not just the desired dissection, but also permanent tissue damage. Carbonization, for instance, occurs when the tissue temperature rises above 100 °C, typically in the surroundings of the incision line [15]. It commonly occurs because of an erroneous selection of laser parameters, e.g. long laser exposure, and results in non-intentional damage of healthy tissues that should have been preserved.

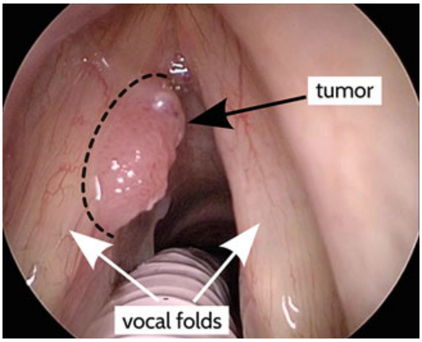

Fig. 1.1 Squamous cell carcinoma of the vocal folds. Image courtesy of Prof. Giorgio Peretti, MD, Clinica Otorinolaringoiatrica, Università di Genova

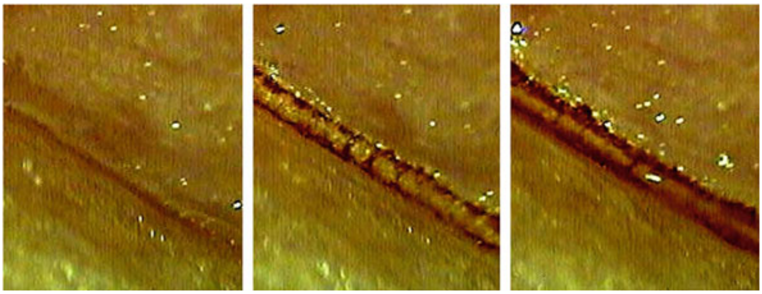

Fig. 1.2 Sequence showing progressive carbonization of soft tissue during interaction with CO_2 laser radiation. Reproduced from [26] with kind permission from Springer Science+Business Media

The onset of carbonization is not easy to control, as it offers limited visual cues: the tissue blackening associated with it (Fig. 1.2) appears once damage has already occurred. To optimize medical outcomes, carbonization should be avoided [15], as it leads to a longer patient healing time and may leave scars, diminishing the quality of surgery [27].

From the simple scenario described above, it is apparent that the control of the incision process relies entirely on the experience and dexterity of the surgeon, who intrinsically establishes the state of the cutting and thereby decides the laser actions to be perform. The interaction between the laser and the tissue is the elemental building block at the core of laser-based surgery: it is through this interaction that incisions are performed. Unfortunately, nowadays there are no technical solutions for the automatic supervision of this process. To this end, a predictive model would be necessary, i.e. a model that allows to predict the outcome of the laser-tissue interaction process is needed. Analytical models of laser-tissue interactions (LTI) are well known [15]: these seem impractical to use in our scenario, as they admit a solution only under very strict assumptions. Furthermore, these models depend on a considerable number of variables representing properties of both the laser and the tissue (e.g. laser wavelength, absorption and scattering coefficients of tissue, tissue thermal conductivity, etc.), that are not straightforward to measure in a surgical setup. If a system is supposed to supervise the state of the LTI, it should rely on inputs similar to those used by surgeons and not on analytical models based on tissue properties. Accordingly, we propose to use models motivated by the capacity of humans to map and fuse diverse sets of information and infer the future state of events.

1.2 Components of the Research

This doctoral dissertation develops at the intersection of three distinct fields of research, as illustrated in Fig. 1.3. The work described here is part of a larger research effort, called the μRALP project [28]. This EU-funded project proposes to redesign and improve the state-of-the-art setup for laser microsurgeries. Through research and development in a range of topics including human-machine interfaces, assistive

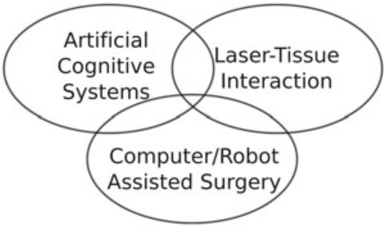

Fig. 1.3 The research presented in this dissertation resides at the intersection of different fields

systems, medical imaging, endoscopic tools, and micromanipulators the project aims to improve the levels of accessibility, precision and safety in this kind of procedures. The ultimate goal is the creation of an advanced surgical robotic platform, enabling surgeons to perform operations that would not be possible using the current technology. The μRALP platform aims to enhance the surgeon's perception of the surgical site and support his decision-making process by means of an information-rich interface based on augmented reality.

In the scope of the μRALP project, the objective of this research is establish the ground for the development of novel technologies for computer-assisted laser surgery. These shall provide the clinician with support for the automatic control/monitoring of laser incisions during microsurgeries. To enable these technologies, here we conduct an investigation of the laser ablation process, and derive models capable of mapping the application of laser light to its corresponding effects on tissue. It is important to point out that the objective of our modeling is not to describe the physical interactions between laser light and tissues. Rather, we shall focus on the analysis and synthesis of higher-level effects, which are relevant from a clinical point of view.

The use of a forward model to predict the outcomes of the laser ablation process is a problem in which analytical modeling is neither convenient nor viable. For this reason, here we explore *cognitive* models, i.e. models that attempt to replicate human cognitive processes for the purpose of predicting the future state of events. Specifically, we develop models of the laser incision process based on the same high-level information used by the surgeons: laser activation, power, pulse duration and exposure time. These models are extracted through the use of statistical learning techniques from data collected during controlled laser experiments.

1.3 Scope of the Thesis

The main contribution of this thesis is the application of a statistical learning approach to infer models of LTI that are straightforward to use in a surgical setup, and which enable enhanced precision in laser-based surgical operations.

1. A model for the estimation of the tissue temperature during laser ablation is derived. The model extends current analytic models in that it accounts for temperature variation induced by a moving laser beam.
2. A model for the estimation of the laser cutting depth during laser incision is extracted. The obtained model extends the scope of application of a similar class of

solutions (steady state models [16]), demonstrating their feasibility for laryngeal laser microsurgery.

3. The inverse model for the laser cutting depth enables different strategies for the controlled ablation of soft tissues. Here we present and validate one such strategy by demonstrating automatic control of laser incision depth on soft tissue.
4. The models of LTI enable the supervision of the laser cutting process, thus enabling the development of practical technologies that assist and guide clinicians during laser microsurgery.

1.4 Outline of the Thesis

This dissertation is articulated into seven chapters, the remaining of which are organized as follows:

Chapter 2 presents the theoretical background of this dissertation. The fundamentals of laser technology and laser-matter interactions are introduced. Particular focus is given to the mechanisms of thermal laser ablation of biological tissues. The equations governing these processes are reviewed and discussed.

Chapter 3 introduces the research questions that motivate the research described in this dissertation. These are related to the use of statistical learning theory to model the laser incision of soft tissues. Materials and methods employed in our investigation are presented here.

Chapter 4 presents a novel methodology to model tissue temperature dynamics during laser incision. This process is modeled through the superposition of Gaussian basis functions, whose parameters are estimated through a nonlinear fitting technique.

Chapter 5 presents a novel approach to estimate the laser cutting depth in soft tissues. A simple linear regression is demonstrated to provide sufficient modeling accuracy for surgical applications of lasers. The inverse model is used to enable the controlled laser ablation of soft tissues.

Chapter 6 presents a practical implementation of the models derived in the previous chapters. This chapter demonstrates the concept of a system capable of monitoring the laser incision process in a real operating scenario.

Chapter 7 concludes this dissertation and provides some suggestions regarding future directions of research related to this work.

References

1. M. Rubinstein, W. Armstrong, Transoral laser microsurgery for laryngeal cancer: a primer and review of laser dosimetry. Lasers Med. Sci. **26**(1), 113–124 (2011)
2. V. Oswal, M. Remacle, Transoral laser laryngeal surgery, in *Principles and Practice of Lasers in Otorhinolaryngology and Head and Neck*, 2nd edn., ed. by O. Vasant, R. Marc (Kugler Publications, Amsterdam, The Netherlands, 2014), pp. 99–116
3. G. Peretti, C. Piazza, F. Del Bon, R. Mora, P. Grazioli, D. Barbieri, S. Mangili, P. Nicolai, Function preservation using transoral laser surgery for T2–T3 glottic cancer: oncologic, vocal, and swallowing outcomes. Eur. Arch. Otorhinolaryngol. Official J. Eur. Fed. Otorhinolaryngol. Soc. (EUFOS) **270**(8), 2275–2281 (2013)
4. H. Sims, T. Brennan, Laser treatment for head and neck cancer, in *Head & Neck Cancer: Current Perspectives, Advances, and Challenges*, ed. by J.A. Radosevich (Springer, Netherlands, 2013), pp. 621–648
5. W. Steiner, P. Ambrosch, Endoscopic laser surgery of the upper aerodigestive tract: with special emphasis on cancer surgery. Thieme (2000)
6. M. Remacle, G. Lawson, M.-C. Nollevaux, M. Delos, Current state of scanning micromanipulator applications with the carbon dioxide laser. Ann. Otol. Rhinol. Laryngol. **117**(4), 239–244 (2008)
7. N. Deshpande, J. Ortiz, D. Caldwell, L. Mattos, Enhanced computer-assisted laser microsurgeries with a "virtual microscope" based surgical system, in *IEEE International Conference on Robotics and Automation (ICRA)*, 2014, May 2014, pp. 4194–4199
8. L.S. Mattos, N. Deshpande, G. Barresi, L. Guastini, G. Peretti, A novel computerized surgeon machine interface for robot-assisted laser phonomicrosurgery. The Laryngoscope **124**(8), 1887–1894 (2014)
9. Y.-T. Wong, C.C. Finley, J.F. Giallo, R.A. Buckmire, Novel co2 laser robotic controller outperforms experienced laser operators in tasks of accuracy and performance repeatability. The Laryngoscope **121**(8), 1738–1742 (2011)
10. H.-W. Tang, H.V. Brussel, J.V. Sloten, D. Reynaerts, G. De Win, B.V. Cleynenbreugel, P.R. Koninckx, Evaluation of an intuitive writing interface in robot-aided laser laparoscopic surgery. Comput. Aided Surg. **11**(1), 21–30 (2006)
11. M. Remacle, F. Hassan, D. Cohen, G. Lawson, M. Delos, New computer-guided scanner for improving co2 laser-assisted microincision. Eur. Arch. Otorhinolaryngol. Head & Neck **262**(2), 113–119 (2005)
12. J.F. Giallo, A medical robotic system for laser phonomicrosurgery. Ph.D. dissertation, North Carolina State University (2008)
13. L. Mattos, G. Dagnino, G. Becattini, M. Dellepiane, D. Caldwell, A virtual scalpel system for computer-assisted laser microsurgery, in *2011 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)* vol. 2011, pp. 1359–1365
14. S.C. Desai, C.-K. Sung, D.W. Jang, E.M. Genden, Transoral robotic surgery using a carbon dioxide flexible laser for tumors of the upper aerodigestive tract. The Laryngoscope **118**(12), 2187–2189 (2008)
15. M. Niemz, *Laser-tissue Interactions* (Springer, Berlin Heidelberg, 2004)
16. A. Vogel, V. Venugopalan, Mechanisms of pulsed laser ablation of biological tissues. Chem. Rev. **103**(2), 577–644 (2003)
17. Y. Yan, A.E. Olszewski, M.R. Hoffman, P. Zhuang, C.N. Ford, S.H. Dailey, J.J. Jiang, Use of lasers in laryngeal surgery. J. Voice **24**(1), 102–109 (2010)

18. Ict—Information and Communication Technologies. work programme 2011–2012. http://cordis.europa.eu/fp7/ict/components/documents/ict-wp-2011-12-en.pdf. Accessed on 03 Mar 2015 (Online)
19. L. Barnes, L. Tse, J. Hunt, M. Brandwein-Gensler, M. Urken, P. Slootweg, N. Gale, A. Cardesa, N. Zidar, P. Boffetta, Tumours of the hypopharynx, larynx and trachea: Introduction, ed. by L. Barnes, J. Eveson, P. Reichart, D. Sidransky, in *World Health Organization Classification of Tumours Pathology and Genetics of Head and Neck Tumours* (IARC Press, Lyon, 2005), pp. 111–117
20. A. Altieri, W. Garavello, C. Bosetti, S. Gallus, C.L. Vecchia, Alcohol consumption and risk of laryngeal cancer. Oral Oncol. **41**(10), 956–965 (2005)
21. J.A. Kirchner, Two hundred laryngeal cancers: patterns of growth and spread as seen in serial section. The Laryngoscope **87**(4), 474–482 (1977)
22. J. Ferlay, E. Steliarova-Foucher, J. Lortet-Tieulent, S. Rosso, J. Coebergh, H. Comber, D. Forman, F. Bray, Cancer incidence and mortality patterns in europe: estimates for 40 countries in 2012. Eur. J. Cancer **49**(6), 1374–1403 (2013)
23. M.L. Hinni, A. Ferlito, M.S. Brandwein-Gensler, R.P. Takes, C.E. Silver, W.H. Westra, R.R. Seethala, J.P. Rodrigo, J. Corry, C.R. Bradford, J.L. Hunt, P. Strojan, K.O. Devaney, D.R. Gnepp, D.M. Hartl, L.P. Kowalski, A. Rinaldo, L. Barnes, Surgical margins in head and neck cancer: a contemporary review. Head Neck **35**(9), 1362–1370 (2013)
24. M. Alicandri-Ciufelli, M. Bonali, A. Piccinini, L. Marra, A. Ghidini, E. Cunsolo, A. Maiorana, L. Presutti, P. Conte, Surgical margins in head and neck squamous cell carcinoma: what is close? Eur. Arch. Otorhinolaryngol. **270**(10), 2603–2609 (2013)
25. S.L. Jacques, Optical properties of biological tissues: a review. Phys. Med. Biol. **58**(11), R37 (2013)
26. D. Pardo, L. Fichera, D. Caldwell, L. Mattos, Learning temperature dynamics on agar-based phantom tissue surface during single point co2 laser exposure. Neural Process. Lett. **42**(1), 55–70 (2015). http://dx.doi.org/10.1007/s11063-014-9389-y (Online)
27. R. Steiner, Laser-tissue interactions, in *Laser and IPL Technology in Dermatology and Aesthetic Medicine*, ed. by C. Raulin, S. Karsai (Springer, Berlin, 2011), pp. 23–36
28. The microralp project, http://www.microralp.eu. Accessed 03 Mar 2015 (Online)