Quantitative Laughter Detection, Measurement, and Classification—A Critical Survey

Sarah Cosentino, *Member, IEEE*, Salvatore Sessa, *Member, IEEE*, and Atsuo Takanishi, *Member, IEEE*

(Methodological Review)

***Abstract*—The study of human nonverbal social behaviors has taken a more quantitative and computational approach in recent years due to the development of smart interfaces and virtual agents or robots able to interact socially. One of the most interesting nonverbal social behaviors, producing a characteristic vocal signal, is laughing. Laughter is produced in several different situations: in response to external physical, cognitive, or emotional stimuli; to negotiate social interactions; and also, pathologically, as a consequence of neural damage. For this reason, laughter has attracted researchers from many disciplines. A consequence of this multidisciplinarity is the absence of a holistic vision of this complex behavior: the methods of analysis and classification of laughter, as well as the terminology used, are heterogeneous; the findings sometimes contradictory and poorly documented. This survey aims at collecting and presenting objective measurement methods and results from a variety of different studies in different fields, to contribute to build a unified model and taxonomy of laughter. This could be successfully used for advances in several fields, from artificial intelligence and human–robot interaction to medicine and psychiatry.**

***Index Terms*—Emotion recognition, human gesture recognition, human–machine interaction, human–robot interaction, laughter, physiological signal processing, sensing.**

I. Introduction

NONVERBAL human social communication has been the subject of study of diverse groups of researchers, from social psychologists [1]–[6] and psychiatrists [7]–[10] to physicians [11]–[20], neuroscientists [21]–[29], and, more recently, engineers and computer scientists [30]–[32]. Researchers have studied and measured human movements to find the communicative meaning of gestures and posture [33]–[36], monitor the wellbeing of specific populations [10], [37], chart social interaction dynamics [38]–[42], or provide robots and virtual interfaces with social intelligence [43], [44].

Laughter is a nonverbal communication signals that plays an important role in several social situations. However, remarkably little is known about this multimodal communication signal. In fact, spontaneous laughter is classified as a semivoluntary action and cannot be easily controlled, voluntarily performed, or suppressed [21]. The possibility to detect, analyze, and classify laughter can lead to progress in a variety of fields, from medicine [12]–[20], [23] and psychology [7]–[10] to robotics [45], [46].

The major problem connected with laughter is that this behavior is both a strong social interaction signal and an expression of internal emotional state [21], [47], [48]. Also, the action of laughing involves the coordination of several groups of muscles, some related to the actual sound production (respiratory muscles, larynx apparatus), some related to visual display (facial muscles), and some other as byproduct of the intensity of the accompanying emotion (arm gesturing, posture alterations) [49].

For all these reasons, laughter has been the object of several studies in different fields, each one of them distinct from the others and aiming to different results. There are qualitative studies mostly referred to its emotional or social valence, using specific nomenclature and a classification typical of the psychology field [50], and quantitative studies, typical of technical [51]–[54] and medical fields [55]–[58], aiming at describing the physiological aspects, muscles involved and sound characteristics, using a completely different nomenclature and classification. The lack of a common foundation, and of a consistent methodological standardization in the study design, stimuli presentation, analysis techniques, and response classification, makes understanding laughter very difficult, especially for researchers in human–machine interaction and affective computing, who need to use quantitative results from the technical literature to infer qualitative characteristics from the social and psychological point of view.

The purpose of this survey is to bring together the different results obtained in different fields, to both present all the possible methods to quantify laughter and try to draw a comprehensive physiological model of this complex human behavior.

II. Method

This study has been undertaken as a systematic literature review on laughter measurement following the original guidelines as proposed by Kitchenham *et al.* [59].

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S. Cosentino is with the Graduate School of Advanced Science and Engineering, Waseda University, Tokyo 169-8050, Japan (e-mail: sarah.cosentino@aoni.waseda.jp).

S. Sessa is with the Graduate School of Creative Science and Engineering, Waseda University, Tokyo 169-8050, Japan (e-mail: s.sessa@aoni.waseda.jp).

A. Takanishi is with the Department of Modern Mechanical Engineering and the Humanoid Robotics Institute, Waseda University, Tokyo 169-8050, Japan (e-mail: contact@takanishi.mech.waseda.ac.jp).

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A. Research Questions

The research questions addressed by this study are as follows:

1) What are the major characteristics of laughter?
2) Which techniques have been used to detect and measure laughter to present?
3) What are the limitations of current methods?
4) For which applications are these methods valid (e.g., might these methods be valid for HRI)?

Answering these questions would provide a solid technical background to be able to choose suitable techniques to observe and quantify laughter for different applications.

B. Criteria of Inclusions

The search process was a manual search online of specific conference proceedings and journal papers, with a combination of a set of keywords: laughter, laughing, laugh, detection, measurement, assessment, evaluation, classification, sensing. Upon a first literature evaluation, when a significant body of research was found, a deeper and more precise search was performed on specific sensing methods, using the keywords laugh coupled with specific physical and physiological sensing techniques. Among the most used techniques used to measure laughter, there are: audio processing, respirometry, pneumography, electromyography (EMG), mechanomyography, functional magnetic resonance imaging, electroencefalography, magnetoencephalography.

The search was performed on the following databases:

1) IEEExplore (ieeexplore.ieee.org);
2) ACM Digital Library (dl.acm.org);
3) Google Scholar (scholar.google.com);
4) Citeseer (citeseerx.ist.psu.edu);
5) PubMed (www.ncbi.nlm.nih.gov/pubmed);
6) ScienceDirect (www.sciencedirect.com).

In addition, the authors systematically examined the findings of ILHAIRE, a two-year EU-sponsored project on laughter study and synthesis (www.ilhaire.eu) and also contacted several researchers directly to enquire and ask clarifications about their previous or current works on the subject.

A number of quantitative studies have been conducted also in the medical field to investigate whether laughter significantly alters the human body physiology and chemistry, especially the immune and pain perception systems. The majority of these studies are preliminary, and many of the claims made are either not fully supported by extensive trials, or very weak in the initial hypothesis. For this reasons, their results are still considered unreliable, albeit basis for further biomedical research [12], [14], [20], [60]–[64]. These studies have not been included in the present survey because they fall out of its scope, which primarily is to report methods to measure, quantify, and classify the behavior itself, and not its secondary effects.

III. Laughter: Expression and Representation

A. Background

Early scientific research studies on laughter were predominantly of a qualitative nature, aiming at describing facial expressions, vocalization, and both communicative and noncommunicative body movement, from a naturalistic point of view [6], [65]–[68].

On the other hand, as a sound, laughter has been the object of quantitative study since the first recorders have been invented [69], [70], and its sound structure and characteristics have been investigated in deep with the most modern techniques of signal processing [51], [52], [71].

In the 1960s, several explorative studies on laughter were undertaken in the medical field, mostly to highlight the mechanisms at the basis of respiration [55], [56], [72].

In the 1990s, with the advent of new technologies, the study of laughter became more systematic, as researchers adopted a more quantitative and computational approach, analyzing video and audio data, often supported by different physiological measurements, such as skin conductance, muscle electrical activation, heart rate, etc. [73]–[80].

These studies also stem from the advancements in Artificial Intelligence, and the spread of robots and automated applications for everyday use: more and more, in fact, virtual agents and robots are required to interact socially and emotionally with humans and, to do that, require numerical data and complete behavioral models.

However, although humans normally process multimodal laughter information unconsciously, but efficiently, mainly with vision and hearing, robot vision and audio processing are still quite limited to process synchronized social information at once [81], and recognition performance degrades drastically in adverse environmental conditions such as noisy or smoky locations, angle or distance of the laughing subject [82]. The situation is even more complicated in a group interaction, when each single participant must simultaneously process social and emotional feedback from several other participants [83]. The integration of physiological and movement data might help to overcome these limitations. Physiological sensors give, in fact, the possibility to record numerical data about various different aspects of laughter, allowing the correlation of multiple expression channels and the development of a unified physiological model on laughter [84], [85].

This quantitative approach is also very useful in the medical and behavioral psychology fields and might help in identifying clinical causes and effects of several pathologies, and in developing treatments to improve the quality of life of specific populations, e.g., cataplectic subjects, subjects with pseudobulbar affect syndrome, and, more in general, subjects afflicted by various neural and cerebral pathologies whose symptoms include gelastic seizures [10], [18], [23].

B. Laughter: A Multimodal Response

Among all the nonverbal social behaviors, laughter is very interesting because it can be elicited by several different stimuli, it is strongly associated with positive emotion and physical well-being, and it is also a form of direct interaction [21], [22].

Unfortunately, even if laughter follows a predictable pattern, it is slightly different depending on the subject, on the conveyed emotional information, and on its social meaning [86]–[90]. This makes laughter very difficult to objectively detect, quantify, and classify.

Technically speaking, laughing is a human movement resulting in the production of a typical vocal sound, laughter. However, it is very important to note that laughter is a highly multimodal expression involving several muscles at once with various outputs: rhythmic abdominal compressions affecting the respiration cycle to produce a modulation of breathing, typical facial expressions, the activation of the phonation system, and often some accompanying communicative gestures, normally related to the intensity of the emotional arousal [21], [31], [49], [91].

As a multimodal activity, laughing is characterized by three major features.

1) vocal emission—laughter sound;
2) facial expression;
3) whole body movement.

Vocal sound in humans is the product of synchronized respiration modulation and phonation movements, and in fact, several studies focused on these activities in correlation with laughter [92], [93].

Even if the big bulk of acoustic information, especially in the frequency domain, has been obtained with traditional methods of audio processing, converging information about the temporal rhythmic structure of laughter has been extracted from different physiological studies as well.

There is a variety of methods that can be applied to measure laughter, depending on the measured expression channel. This survey contains the results of several studies on laughter, according to the different expressive pattern considered:

1) acoustics: emitted sound—laughter;
2) respiration;
3) phonation;
4) facial expression;
5) whole body movement.

Interestingly enough, even if more recent studies take into account more than one expression channel, in an attempt to multimodal detection, analysis, and—especially—synthesis of laughter, very few take into account all its five major expression channels simultaneously.

C. Laughter: Temporal Segmentation

The multidisciplinarity of laughter studies has unfortunately led to confusion in terminology. Depending on the study, terms are either not clearly defined, or they are used with different meaning in different studies. To clarify the situation, in this paper, we will generally adopt the terminology proposed by Ruch and Ekman [49], except for the definition of episode and bout, more consistent with other studies [21], [22] (see Fig. 1).

1) *Laughter episode* is the term used to refer to the whole multimodal event, including not only the vocal but also all the other correlated elements. A laughter episode can contain one or several laughter bouts. The laughter episode is then subdivided in three phases:
   a) *onset*, the prevocal facial part, which can be a long, building up smiling expression, or *vice-versa* a very short transition in explosive laughter;
   b) *apex*, the period in which the vocalization, or, in case of unvoiced laughter, the forced rhythmic exhalation occurs. It is normally composed of one or more laughter bouts interspersed with pauses, to allow inhalation for lung refilling.
2) *Offset*, post-vocalization period.
3) *Laughter bout* is used to denote the period of continuous vocalization or rhythmic exhalation, and it is composed of one or more laughter calls, typically around four.
4) *Laughter call* is a rhythmic expiratory pulse composing the structure of a "typical" laugh. In voiced laughter, it is the alternating rhythmic unvoiced-voiced pattern composing its typical acoustic phonetic structure. In particular, in phonetics studies, can be assimilated to a consonant-vowel *syllable* structure [94]. It is generally composed by an aspiration phase, or unvoiced consonant (H), and a vocalization phase, or voiced vowel, not necessarily present (unvoiced laughter). It is also referred to as *interpulse interval* [49], *laugh event* [95]:
   a) *pulse*: in voiced laughter, it is the duration of the vocalization phase within the laughter call. Depending on the study, the vocalic segment is named differently: *utterance nucleus* [49], *vocal peak* [95], *burst* [71], *note* [96], *call* [51], or *syllabic vocalization* [97]. According with phonetic terminology, *vowel* is used [51], [57], [98], but also in contrast, *syllable* [96] or even *plosive* [54] occur. At the level of laryngeal movements a pulse can be further split up into *vocal cord vibratory cycles* and even further into their *contour*: phases in which vocal cords are opening, closing, or closed. [58];
   b) *interpulse pause* [49] or *intercall interval* [51]: the duration of the nonvocalization phase within the laughter call. This phase is also called *unvoiced consonant*, but in fields other than phonetics, the unvoiced consonantal segment is seen as pause or interval rather than as an aspiratory phase. Provine [21] uses a mixed terminology, calling it interval but denoting it as a "breathy aspiration."

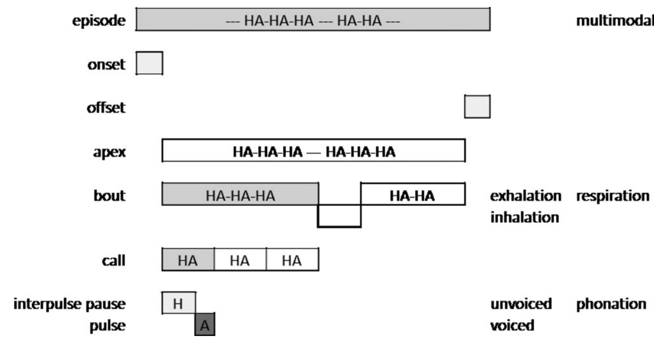

Fig. 1. Laughter temporal segmentation.

IV. Laugher Characteristics

A. Emitted Sound—Laugher

Quantitative acoustic analysis of laughter has begun as soon as the first sound recorders were developed. One of the first studies is from Boeke in 1899: he recorded his own laughter on an Edison Sonograph [69], [70]. Laughter acoustic analysis has progressed from simple analysis of the temporal and frequency characteristics of its sound to the extraction of complex features for emotional connotation used mostly in the speech recognition field.

Even if laughter is a stereotyped sound, meaning that it can be easily recognized and classified as "laughter" regardless the culture, the age, and other differences among the laughing subject and the audience, laughter is a repertoire of highly variable vocalizations that includes qualitatively distinct sounds [86]. We will analyze this more in deep in the section on laughter classification.

Notably, bout length and call structure—number of pulses, duration of pulse, and interpulse pause—depend both on biological factors and on laughter valence and informative content [88], [99], [100]. Laughter appears in children at about four months of age and at the beginning produces very short bouts composed of only one call or two [95], [97]. The maximum number of calls contained in one bout increases with age [21], [71], as it depends also on lungs capacity.

We know from the literature the following [101].

1) Temporal Characteristics: Typically, a bout of hearty laugh is composed by around four to five calls (syllabic segments) [47], [51].

The minimum number of calls in a bout is 1 [51], [95], while the maximum ever recorded number of calls in a bout is 25 [71].

The number of calls per second averages to 4.5/s [49], [51]. The average duration of a call is about 220 ms [49], [51], the average duration of the interpulse pause (unvoiced consonant) is 145 ms [47], [51], [53], [94], and the average duration of a voiced pulse is 75 ms [47].

A significant negative correlation was found between call position in a bout and its pulse duration: pulses late in a sequence tend to be shorter than those occurring earlier, especially in long bouts, after the fourth call [47], [51].

A significant positive correlation was found between call position in a bout and the duration of its intercall pause: calls late in a sequence tend to have a longer pause than those occurring earlier, after the fourth call, in long bouts [47], [51].

The average unvoiced/voiced ratio of calls is 1.75, but it is positively correlated with call position in a bout: it can start as low as 0.5 and reach past 2.5, especially in long bouts [47], [51].

A significant negative correlation was found between call position in a bout and its pulse amplitude: pulses early in a sequence tend to be louder than those occurring later, in a strong decrescendo, probably due to the decrease of available air supply [47], [102].

2) Frequency Characteristics: The fundamental frequency F_0 of laughter is considerably higher than in modal speech. Provine and Bachorowski report $F_{0ML}\sim$278 Hz for male and $F_{0FL}\sim$480 Hz for female laughter against, respectively, $F_{0MS}\sim$120 Hz and $F_{0FS}\sim$220 Hz for modal speech [47], [51].

Others report much lower values, but, consistently, laughter fundamental frequency F_{0L} is about 20% higher than fundamental frequency for modal speech F_{0S}, for both male and female [54], [71], [90], [94], [103], [104].

Pulses—laughter vowel-like vocalizations—have very different kinds of sonograms compared to vowel in speech: vowels are characterized by dominant harmonics of the vocal fundamental frequency F_0, while laughter components are far more disperse and entropic. Although voiced pulses may have frequencies above 16 kHz, most power is contained below 8 kHz [21], [52].

Secondary formants have been measured in very few studies and, in average, are: $F_1\sim$620 Hz, $F_2\sim$1750 Hz, $F_3\sim$2500 Hz, $F_4\sim$3700 Hz, $F_5\sim$4550 Hz [51], [90], [94], [103]. Typically, in female, laughter secondary formants are slightly higher than in male [51], [88], [94], [103]. It is in fact observable that the spectral peaks are less numerous and closely spaced in the female than male laughter, a finding consistent with the higher fundamental frequency and pitch of the female laugh [21].

The study of dynamic prosodic parameters of laughter should not be overlooked. The main prosodic features of a sound signal are variations in pitch, loudness, quality (perceived shape of acoustic formants), and duration patterns (rhythm) [105]. Prosodic features of speech reflect both the speaker's individual voice characteristics and speech emotional content. These are very informative and have, therefore, been used in laughter recognition and analysis in several recent studies. The trends were the following: the F_0 measures are higher for amused laughs than for polite laughs; the duration is also highest for amused laugh, the percent of unvoiced frames is the highest, and also, the energy is the lowest for embarrassed and ironic laughs. These trends should be confirmed with a larger database [106].

B. Respiration

A respiration cycle consists of two phases: inspiration and expiration. During respiration, in resting condition, adults will complete 12–18 respiration cycles per minute [107].

Generally, upper trunk muscles are used for inspiration. The primary inspiration muscle is the diaphragm, supported by other accessory muscles of respiration.

Lower trunk/abdominal muscles are instead used for expiration [107], [108].

Reliable pulmonary ventilation measurements require either registering the volume of gas taken into or exhaled from the lungs (direct spirometry), or monitoring the volume displaced by a portion of the body sealed within inconvenient equipment. These methodologies interfere with normal speech and breathing and are not well tolerated during prolonged recordings. For these reasons, indirect methods have been developed: impedance pneumographs and magnetometers [109]. EMG can also be used to evaluate the activation of specific involved muscles [110].

Studies of laughter as a respiration act confirm the temporal results obtained with acoustic analysis and draw a partial physiological and muscular model of this behavior.

Laughter is generally performed at low lung volume: no matter where in a respiration cycle a person is, a bout of laughter typically begins near functional residual capacity, the lung volume after a normal expiration, with an initial forced exhalation, and it is terminated near or sometimes even over residual volume (RV), the remaining air volume in the lung after maximal voluntary expiration [49], [93], [111]–[114].

The initial forced exhalation is followed by a sequence of repeated expirations, laughter calls, which may or may not be vocalized. In long laughter episodes, after reaching or passing the RV, inhalations to refill lungs separate subsequent bouts [49], [115].

With the use of a pneumograph to quantify the respiratory differences during emotional expressions it has been found that, in terms of the analyzed features, laughter scores very similarly to pain. However, the actual recorded respiratory wave is very peculiar and differs from all the other emotional waves by its characteristic modulation of the expiratory phase [11]. A subsequent study, using a dynograph with a volume/pressure transducer, and with a larger pool of subjects, found that respiratory patterns, in terms of sudden changes in thoracic and abdominal circumferences, can be good predictor of laughter only in female subjects [72]. Another study, however, with the same technique found significant differences in basic emotional respiratory patterns for both male and female subjects [116].

In addition, during expiratory activities like coughing, singing, and laughing, the diaphragm is constantly contracted, with a more or less homogeneous intensity, while the transdiaphragmatic pressure increases. These findings have been confirmed using invasive EMG and a gastric balloon to measure respiration phases, muscle activation, and transthoracic pressures, but also with noninvasive 3-D optoelectronic plethysmography to monitor lung dynamics [93]. It has then been hypothesized that the diaphragm acts as an antagonist for the abdominal muscles, controlling their expiratory force. This is particularly interesting for measurement/detection purposes: measuring the movement of abdominal muscles should bring more information on laughter than the movement of diaphragm [55], [56].

In fact, when using EMG on abdominal and thoracic muscles to discriminate various respiratory and nonrespiratory activities, a better signal is generally acquired on lower abdominal muscles, best on the lower transversalis. Posture also affects results: signals acquired in the supine position are much weaker than the ones acquired in upright position [117]–[119]. Good results are obtained also using accelerometers [120]. However, laughter is successfully measured with EMG also on the xyphoid process [74], [77], [121], traditional position to measure diaphragmatic activities for clinical respiration measurements.

C. Phonation

Phonation is the process by which the vocal folds produce certain sounds through vibration. Vocal folds are located within the larynx at the top of the trachea, attached posteriorly to the arytenoid cartilages, and anteriorly to the thyroid cartilage. Their inner edges are free to vibrate to produce vocal sound, while their outer edges are attached to muscles in the larynx responsible for their movement. The pitch of the voice is defined as "rate of vibration of the vocal folds." As the number of vibrations per second increases, so does the pitch, meaning the voice would sound higher [107].

Phonation comprises mechanical and aerodynamic phenomena. Vocal fold movements can be observed directly, visually, while the aerodynamic processes can be examined only indirectly [122]. There are several techniques for the evaluation of laryngeal behavior, unfortunately mostly invasive or not very ecological, and thus uncomfortable for a subject. Using these techniques, the acoustic structure of a typical vocalized laughter bout, produced by a series of rapid, continuous, stereotypical movements of the larynx, has been studied. Four phases can be individuated [58].

1) *Interpulse pause*: unvocalized pause between the vocalized pulses. The arytenoid cartilages are open allowing the breath stream to flow through the larynx, and the vocal cords remain still.
2) *Adduction phase*: The arytenoid cartilages move the vocal cords toward each other closing the glottal space, and the vocal cords begin to vibrate.
3) *Vibration phase*: Vocalized pulse, vibration of the vocal cords.
4) *Abduction phase*: Opening of the arytenoid cartilages

The dynamics of larynx during laughter has been analyzed very precisely using invasive intramuscular EMG [114]. During adduction, the thyroarytenoid and the cricothyroid muscles close the glottis, the arythenoids approach each other at a constant rate, and the vocal folds start vibrating while they are still not fully closed. Instead, during abduction, the posterior cricoarytenoid muscle is responsible for the opening, and the vocal folds are still vibrating when the abduction phase begins. The glottis is widely open at the end of a pulse, and no glottal stop occurs. Thyroarytenoid and cricothyroid muscles during adduction, and posterior cricoarytenoid during abduction, operate as antagonists and contract at the same frequency with a phase difference of 180°.

With high-speed photoglottography, it has been found that a vocalized pulse can contain as low as five vocal folds vibratory cycles to more than 15, representing time periods from 30 to 100 ms when the frequency is 150 cycles/s [58]. Pitch alterations, instead, are not achieved by changes in the rhythmic glottal valving, but with different supraglottic configurations and laryngeal elevation [57].

Changes in the fundamental frequency F_0 might be determined by multiple factors: the shortening of vocal tract length, due to lowering or lifting of the larynx [57], [123], or to protraction or retraction of the lips [124], the tension and lengthening of vocal cords, and the variation of tracheal pressure which can, but not always, be temporally correlated with laryngeal adductors [114].

As previously reported, acoustic analyses also document changes in fundamental frequency between pulses; typically, there is a progressive increase in call duration and decrease in pitch and intensity in later pulses of a bout. These findings are supported by several studies, using different techniques: fiberscopic videolaryngoscopy, vidoendoscopy, electroglottography, and acoustic analysis [57], [114], [125], [126].

Some researchers analyze laughter from a pure phonetic point of view [127], drawing an interesting chart of larynx states during laughter and devising a pure phonetic model of laughter

[128]. This model is particularly important because it could be the basis for acoustic automatic detection and classification of laughter using pure phonetic theory.

Other studies use instead phonetic analysis to highlight the main differences between laughter and speech. For example, there are significant differences between laughter and speech not only in mean pitch but also in the ratio of the durations of unvoiced to voiced portions [129]–[131]. Moreover, using electroglottography, it has been demonstrated that speech and laughter have substantial differences in α, β, strength of excitation (SoE), and F_0 contours [132]–[134].

D. Facial Expression

Facial expression is a powerful way to convey emotions in human interaction. Therefore, there is a huge quantity of works related to facial expressions, their analysis, and discrimination. However, detecting, and especially measuring and classifying laughter only from the face, is very difficult, due to the complexity and range of possible facial expressions. For example, smile and laughter are very similar and nearly indistinguishable in 2-D images or by facial EMG (fEMG) analysis. For this reason, methods for laughter recognition from facial expression should be integrated with another data channel, for example, rhythmic movements of head or shoulders, or the audio—especially in the case of large audio–visual data corpora—or the respiration [77], [135]–[140].

There are basically two methods to detect, measure, and classify facial expression: visual image processing or fEMG signal analysis.

Due to the later development of precise visual analysis technologies, still under way, fEMG analysis has a longer history, despite being more cumbersome and invasive. Also, its range of application is wider, as it can be used both in the medical and robotics fields. In fact, one of the first researchers, who analyzed laughter physiologically in the scope of a deep analysis of facial expressions and their relationship with emotions, was Duchenne, more than a century ago [19], [141], [142]. He used electrical stimulation on corpses to separately activate each facial muscle, documenting the resulting expression. He then reproduced, by electrical stimulation of precise sets of facial muscles, several expressions on humans to study the perceived "genuineness." His work was particularly accurate, and his name has been associated, since, with spontaneous and mirthful laughter [22], [25], [27], [49], [143].

About 50 years ago, Sumitsuji took over the challenge, developing a very precise and useful fEMG system. The work of Sumitsuji is particularly interesting. He first proceeded analyzing the facial muscles one by one, verifying the difference in muscular tone and, thus, signal, in standing and lying positions [144]–[146]. Then, he went on exploring laughter and, especially, differences in normal and pathological laughter, with schizophrenic patients [10], [147], [148]. He observed all the facial muscles involved in laughing, draw several charts, and confirmed that the muscular mechanisms at the basis of pathological and normal laughter are very different. He also affirms that spontaneous laughter originates from a "light surprise," highlighting the similarities between the surprised expression muscular pattern and the initial laughing muscular patterns [149].

In a subsequent study, EMG on frontalis muscle was used to verify that its activation is definitely higher during mirthful experiences. A positive correlation between arousal and facial muscular tension was then discovered [150]. In another study, instead, long-term activities of the masticatory system, the masseter and temporal muscles, were recorded for medical purposes [151]. This technique allowed to distinguish between several functional and parafunctional activities, especially from the temporalis EMG. However, the parameters examined did not allow distinguishing univocally laughter either from the masseter or from the temporalis EMG.

Other studies instead proposed a method to evaluate emotions using fEMG, arguing that EMG signals could provide information about suppressed facial expressions that could not be observed visually [152]. In fact, analyzing fEMG of subjects when they suppressed their laughter, it has been reported that several subjects contract their depressor anguli oris muscle when they were about to laugh [80], [153].

A revolution in the visual facial expression quantitative analysis starts in 1977, when Ekman and Friesen developed the Facial Action Coding System (FACS) [154], a system to taxonomize human facial movements, based on the work of Carl–Herman Hjortsjö [155]. FACS defines action units (AUs) and action descriptors (ADs), producing specific facial expressions, and their temporal segments. AUs are defined as contraction or relaxation of individual muscles or groups of muscles. ADs are unitary movements that can involve the actions of several muscles to produce a specific expression. However, the muscular basis and specific behaviors have not been distinguished for ADs as precisely as for the AUs. FACS is a standardized index of facial expressions, but does not actually provide biomechanical information about muscles activation. FACS has become a very powerful tool to detect and classify facial expressions and is actually in use in a variety of fields. For example, FACS can be used to distinguish feigned and spontaneous smile and laughter: the insincere and voluntary so-called Pan-Am smile, a contraction of the zygomatic major alone; and the spontaneous and involuntary Duchenne smile, contraction of zygomatic major and inferior part of orbicularis oculi [19], [156], [157].

FACS is becoming widely used as a valid model for both facial expressions classification and synthesis, especially in robotics, also because it is extremely ecological and does not require direct sensors placement on the subject.

One of the more complete works based on FACS is the one of Niewiadomski and his group [158]. Niewiadomski introduces 12 facial measures (D1–D12) mapping the motion capture data of the AVLC corpus, annotated with intensity values. Relying on annotated intensity values, he mapped FACS AUs with laughing expressions, according to its intensity.

E. Whole Body Movement

Laughing is a whole-body phenomenon involving several distinctive body movements. Some of the body movements are necessary for the actual respiration modulation and laughter production: bending of the trunk, movement of the head, rhythmical movement of the muscles responsible for respiration and phonation. Some other are only bound to express the depth of emotional arousal, and are idiosyncratic, e.g., clutching or slapping of the abdomen or legs [49]. Some movements can also be induced by the cultural background of the subject, e.g., Japanese women use to cover their mouth when they laugh [159].

Probably because of this, there are still very few studies on the plethora of emotional movements surrounding laughter, reporting precise values, and ranges. This also depends on the relatively recent diffusion of wearable sensor systems and complex methods of image recognition, able to record and process multiple movements simultaneously [160]–[162]. These systems are still mainly used for detection and classification, rather than quantitative feature analysis, so they will be discussed in the next section. However, this field of study has acquired a new level of importance with the necessity of record precise movements for reproduction and synthesis purposes [163].

There are, as said in the introduction, few studies in the medical field, whose aim is to establish the effects of laughter—especially mirthful laughter—on the general body health. These studies are too sparse and unreliable due to various flaws in the experimental methods, so they are omitted from this review. However, preliminary quantitative studies on the influence of laughing on the cardiovascular system, heart rate, galvanic skin response, and muscular tone offer interesting insights and propose original quantitative methods for real-time laughter detection and analysis.

An interesting direction for further research is the study of the relationship between whole body muscular tone and laughter. Although Chapman found a positive correlation between arousal and facial muscular tension, several medical studies seem to suggest a negative correlation between muscular tone and laughter, providing scientific basis to the folkloristic saying “weak with laughter” [60].

On this basis, Overeem *et al.* decided to investigate the effect of mirth and laughter on muscular tone, in the scope of finding the triggers of narcolepsy and cataplexy [164]. They used Hoffmann’s reflex (H-reflex) measurement on the leg, a common technique to investigate the neurologic basis of narcolepsy [165]. They found that also in healthy subjects, laughter caused mean H-reflex amplitude to decrease compared to neutral tasks, different respiratory maneuvers, or fake laughter. Also, the decrease of H-reflex amplitude seems to be proportional to laughter intensity [18], [23], [166]. They then hypothesize that H-reflex is depressed by mirth, so it is a good technique to detect genuine laughter.

V. Laugher Social Perception, Classification, and Automatic Recognition

Laughter recognition and classification is very complex, all the more because of its multimodal valence. It is also tightly intertwined with human laughter perception as a social signal, which is subjective and thus very difficult to model and automatize. The problem can be tackled at different degrees of depths: distinguishing laughter from other social communication signals (speech, gestures, nonverbal social behaviors), distinguishing laughter by the precise communication information it carries (conversational semaphore, emotional expression, pathological reaction), and classify different laughter types and their emotional meaning.

Automatic detection and recognition of laughter has been successfully achieved, with a reasonable degree of accuracy, with different methods, in several fields and for a variety of applications. Classification of various laughter types according to their communicative meaning or emotional content is instead a more difficult problem, it requires background from different fields, and would immensely benefit from a unified model of laughter.

A. Detection and Automatic Recognition

There are several on-going projects on laughter—and, more in general, emotional—recognition systems. The majority of them started in very recent years, with the development of more portable and affordable sensors and the need of a more natural human–machine interaction.

Shimizu *et al.* [84] used one of the first multimodal laughter detection system, based on his previous work with Sumitsuji, comprehending fEMG (zygomatic muscle), GSR, plethysmograph, pneumograph, accelerometer, and audio to compute a total body laughter index (BLI). It was used for various studies on different populations, also a measure of depression levels and to distinguish pathological from normal laughter [10], [148]. It is the most complete system developed so far. It is also not very ecological, as it was used mainly for medical purposes, and quality of measurement was preferred over subject’s comfort.

Drugman *et al.* [167], [168], instead, developed an interesting multimodal system composed by an ECG, a thermistor for the thermal flow at the nose, a respiratory belt, a dual-axis accelerometer, a contact microphone, and an audio microphone to detect cough from a set of different respiratory maneuvers, including laughter. He compared the effectiveness of these sensors for the classification of coughing and found that the most significant features for the classification are extracted with audio processing techniques. Nevertheless, even if the best performing sensor for classification is the audio microphone, each one of the other sensors contributes to improve the reliability and robustness of the whole classification system, and the absolute best classification performances are obtained using all the sensors.

These types of system are very effective in case of clinical studies, as they synchronously capture several physical and physiological aspects of laughter, but are not very comfortable for the subject, thus interfering with her psychological state.

Soleymani *et al.* [73] and Canento *et al.* [85] developed a fairly complete, but more general, measurement system to classify the subject’s emotions, which could detect laughter as an emotional expression. Tatsumi *et al.* [80], instead, developed a complete multimodal measurement system to specifically detect laughter and, in particular, hidden/suppressed laughter. This system is particularly interesting to study the characteristics and effects of suppressed laughter, which is particularly hard to detect with other methods, such audio or video analysis.

In fact, with the increasing growth of computational power, the spread of video and audio processing devices, coupled with the need of more natural human–machine interfaces, the studies on laughter detection via acoustic and visual data have multiplied. Several researchers used acoustic processing to detect and distinguish laughter from speech [83], [102], [169]–[175]. The best performances—from 70% to 90% correct classification rate—have been obtained using Mel-frequency cepstral coefficients and perceptual linear prediction over standard audio spectrum features, and combining classifiers that use both spectral features and prosodic information. This is not very surprising as laughter is tailored on the human hearing apparatus.

Many researchers also used combined audio and visual facial expression data for laughter detection. Two are the major findings of Petridis and Pantic [136], [137], [176]–[181]:

1) For both synchronized feature level fusion and decision level fusion types of classification, the inclusion of temporal features improves classification performance over a static feature set performance.
2) Audiovisual laughter detector outperforms single-modal detectors when temporal features are used. When static features are used, only the decision level leads to significant improvement over single-modal laughter detection.

Ito [182] confirms this second finding using a decision-level fusion classifier with only static features. Scherer [75], [183], Korb [184], and Schwenker *et al.* [76] found that the introduction of video data significantly increases the computational burden, and not necessarily improves the performances. However, it improves the robustness of the system especially in case of noisy or missing audio data. A second interesting finding was that support vector machine performs better for offline analysis, while hidden Markov model (HMM) and echo state networks perform better for online detection and recognition and can be used for automatic segmentation of audio data. Niewiadomski [185] and Mancini [31], [78], [91] use, instead of facial expressions, the rhythmic movement of shoulder as a visual laughter cue to compute the BLI.

Another interesting work is the one of Matsumura [186], who uses a bone conducting microphone on the neck to distinguish laughter from speech, measuring the number of syllabic vocalization per millisecond.

Englebienne *et al.* [38]–[40] and Vossen [79] use a single accelerometer on a badge hung at the subject's neck to classify various social activities, with a correct classification rate of over 70%. The system is extremely ecological but not really reliable and useful for finer detailing.

Other researchers [74], [77], [118], [119], [121], [140], [187] used sEMG on face or face and trunk, with detection rates from 70% to 90%.

B. Human Perception, Classification, and Emotional Valence

Classification of laughter types is a difficult task, and we humans also might fail at it without additional information on the contextual situation in which laughter is produced.

In fact, Milford [103] proves that laughter acoustic responses are different dependent on the eliciting stimulus, identifying two main categories: quieter and lower pitched laughter of tension-release and social contexts, as opposed to longer, louder, and higher in pitch laughter in response to humor and tickling. However, stripped of contextual information, judging subjects classified correctly only 36.3% of listened laughter sounds. Also, correct sex identification rate was only 67.5%, very poor considering that very little acoustic information is necessary for sex identification of the speaker [188].

Urbain reached a relatively good accuracy rate of 86.3% for voiced calls and 87.4% for unvoiced ones, albeit still lower than what can be achieved with speech vowels [113].

Bachorowski and Owren [86] divide instead laughter depending on glottal and respiration parameters in three main types: snort-like, grunt-like, and song-like. Song-like laughs, with features such as abrupt rise times, high F_0, significant F_0 modulation, and perhaps acoustic nonlinearities seem to be particularly effective in engaging listener response systems. They found that listeners had significantly more positive emotional responses to voiced than to unvoiced laughs.

In fact, Laskowski and Burger [83] state that assimilating unvoiced laughter to silence, instead that clustering it together with voiced laughter, improved the recognition of emotional hotspots in audio conversations.

However, the analysis of laughter cannot be reduced to voiced or unvoiced discrimination, because selected acoustic features and emission rate of laughter vary not only according to social context, but also to social relationship [51], [96], [98].

Szameitat *et al.* [88], [89], [99] analyzed the expression of four different emotions in laughter, finding that they differ in a variety of acoustical parameters, and that they can be classified accurately 84% on the basis of a small parameter set. Moreover, emotional acoustic profiles are not unique to laughter, but are similar to the ones for emotional expression in speech. Erickson [189] found that happy and sad emotional laughter and speech tend to be similarly perceived and so often confused.

Griffin *et al.* [33], [162] used avatars animated with motion capture data to study the observers' perception of different laughter types (hilarious, social, awkward, fake, and nonlaughter) based on body movements alone. Significant differences in torso and limb movements were found between animations perceived as laughter and those perceived as nonlaughter. Hilarious laughter also differed from social laughter in the amount of bending of the spine, the amount of shoulder rotation, and the amount of hand movement.

In addition, there are several gender differences in the use of laughter. For example, Bachorowski found that, more in general, variability in individual male laughter is associated with his relationship to his social partner—i.e., friend or stranger—whereas individual female laughter is more closely associated with the sex of her social partner. More in detail, Provine found that, in a social context, speakers tend to laugh more than their audiences of the same sex. When, instead, speaker and audience are of opposite sex, females are the ones who laugh more. In fact, a typical male speaker would laugh slightly less often than his female audience, while a female speaker laughs significantly more than their male audience [22].

At the same time, human perception of laughter is a complex mechanism. Kipper and Todt [190]–[192] used artificially modified human laughter to study the perception of laughter. They variated pitch and duration of voiced pulses and combined them in six-call bouts with different characteristics. They found that, presumably, perception of laughter is a two-step process. First, a "recognition mechanism" assesses a given utterance as laughter, based on the parameters of vocalization: the more the vocalization is standardized, the less likely it was rated as a genuine laughter. After that, changes in acoustic parameters within a laughter series are used to evaluate the quality of laughter, and these variations are responsible for the contagious effect of laughter.

Chun [29], instead, studied the brain response to laughter. He found significant differences in the perception of laughter in different sexes, hypothesizing modulating effects that the sex of a speaker might have on brain responses in male and female listeners.

Armony [193] showed that, compared to emotional visual stimuli, all emotional vocalizations, either positive or negative, influence significantly the episodic memory.

VI. Laughter Synthesis

Synthesis is still at its beginning. There are two main research directions: synthesis of the acoustic features and of the visual characteristic of laughter.

Ishizaka and Flanagan [194], [195] developed a very detailed two-mass spring model for the synthesis of generic vocal sounds. Sundaram and Narayanan [196], [197] applied a similar model for the synthesis of laughter: they synthesized vowels through linear prediction and modeled rhythmic intensity curves with the equations governing a mass–spring system.

Lasarcyk and Trouvain [198] compared two methods for laughter synthesis: one based on diphone concatenation (trained on speech data), the other was a 3-D articulatory modeling of the vocal organs. Synthetized laughter using both approaches is perceived as natural during conversation, with diphone concatenation seemingly perceived as more natural. However, during perceptual experiments carried out with questionnaires, synthetized laughter was rated by listening subjects as not natural, compared with natural laughter, especially when listened in isolation, without contextual supporting dialog.

Oh and Wang [199], based on the work of Bachorowski and Owren [86], Kori [200], and Szameitat *et al.* [88], [89], [99], produced synthetic laughter variating several vocal parameters to obtain specific emotional connotations. They used higher level descriptors and prioritized preserving melodic features of laughter over attaining realism. Reported results suggest that they were successful in transmitting different emotional messages; unfortunately, no precise data are presented.

In all cases, synthesized laughs were perceived as significantly less natural than human laughs. Recently, the use of HMMs trained on laughter phonetic transcription was investigated [201]. Using the same evaluation process as Sundaram and Narayanan, it was shown that, although actual human laughs are still out of reach, HMM-based laughter synthesis yields higher naturalness results than the previous methods.

Few models of laughter animations were developed recently. Cosker and Edge [202] and Niewiadomski and Pelachaud [158] proposed a set of features for facial display of laughter, based on FACS. Trutoiu *et al.* [143] stated that a realistic modeling of facial expressions, in particular smiles, must contain nonlinear velocities to be perceived as realistic.

DiLorenzo *et al.* [203] were the first to tackle the problem of reproducing graphically the body movements associated with laughter. Following the work of Luschei and colleagues, they isolated the different trunk muscles involved with respiration and laugh production and modeled the trunk as a combination of rigid and deformable elements. Defining the relationship between lungs pressure and laughter phases, derived from the amplitude of the audio signal, the model computes the volume modifications on the basis of the audio data.

Niewiadomski *et al.* [185], [204] followed with a 2-D reconstruction of rhythmic body (e.g., shoulder) movements based on appropriate harmonics. This model is part of a more complex complete interacting virtual avatar animation, integrating rhythmic body movements with other synthetized laughter features, like audio and facial expression. The system is able to detect and process human laughter and respond with a complete synchronized laughing motion with a comparable intensity [205], [206].

VII. Discussion

This section discusses the main findings and the issues emerged from the studies investigated. Here, we will enumerate the established properties of laughter and point out the areas in which further research is needed.

Laughter studies, even at technical or clinical levels, must take into account that laughter is an emotional expression. Emotional expressions are very difficult to elicit, assess, and quantify reliably. The problem of laughter classification is strictly related to human laughter perception and can be assimilated to classification of affective body expressions, with all the problems surrounding a field in which a real ground truth is not available: self-report is not reliable, external judgment is subjective and—as demonstrated—often very poor due to the lack of contextual information, and the information itself can be distorted in unforeseen ways due to nonecological experimental conditions.

A. Detection, Analysis, and Classification

Detection, analysis, and classification of laughter can be used for a variety of studies and applications. It obviously can be used to build laughter-aware intelligent machines, which can incorporate emotional laughter information processing for a more human-friendly machine interface. But it can also be used for medical purposes, in particular for the study of both physical and mental pathological conditions. In this scope, a lot must still be done to uncover all the physiological and mental changes related to this elusive behavior. In particular, it is advisable to unify the more advanced works on acoustic analysis [51], [86]–[90], [99] to the still preliminary studies on respiratory and physiological changes (muscle effort, H-reflex) [18], [23], [92], [93], [111], [112], [116], [166], [207] and combine more specific studies on related facial expression [19], [144], [145], [148]. These types of multimodal works are still very few and far from offering a complete vision of laughter in all its aspects. Being able to associate precise acoustic contour and bodily expression to mental states should open a bright path to less invasive diagnostic methods for several pathological conditions and to build a unified model of laughter as a behavior carrying different emotional and social meanings, depending on the context.

In addition, even if audio and video data based systems are generally the most ecological, as they allow to monitor subjects moving and interacting freely, these systems can raise privacy concerns, especially in the case of applications for laughter aware intelligent machines and interfaces. Individual wearable systems using body movement data, relying on well-established body movement-emotional state models, can help addressing these concerns. In this sense, data and results drawn from studies using invasive but more precise techniques can help to build a precise physical and physiological model that can be then used to monitor these changes with less precise, but more ecological, methods.

B. Emotional Valence

The studies surveyed have shown that laughter is elicited by several stimuli, it is a multimodal emotional expression, and it can be associated with several emotions. Given that laughter itself can be voiced or unvoiced, and even suppressed or "hidden," it has been established that the body also is an important modality to detect and recognize it. It is worth pointing out that in some of the studies surveyed, mostly related to automatic detection and classification of emotions, the reductive assumption that laughter is associated with joy—and crying with sadness—is still present. While this is surely true under some conditions, it has been proven to be not universally true, so those conditions must be verified before proceeding further. In this sense, laughter generally share a core set of features associated with the specific associated emotional category, independent of the actions performed. In this respect, study of the emotional content of laughter falls in the wider category of studies on recognition of emotion from body movements [32], [34], [36], [208]–[210], whose idea at the base is to differentiate the same action performed in a slightly different way depending on the subject's current emotional state, and to model the emotional content as variations in a repeated cyclical pattern. These types of studies on laughter differences are almost absent. Additionally, laughing produces a vocalization, laughter, which can be studied with the same techniques used in audio processing and speech recognition, adding a degree of precision, and giving a more complete image of the emotional state and changes of the subject.

C. Synthesis and Modeling

Synthesis and modeling of laughter is the next logical step to build machines with more user-friendly and natural interfaces.

Again, it has been shown that it is of uttermost importance the perfect integration and synchronization of both acoustic and visual perceptual channels to obtain a natural impression. The synchronized mapping of laughter acoustic temporal and intensity parameters to physical human movement and physiological changes needed to produce that type of vocalization would lead to a dramatic improvement of the perceived naturalness of laughter as a whole-body behavior.

VIII. Conclusion

The purpose of this paper has been to examine laughter as a multimodal social and emotion expression behavior to describe its characteristics and to present all the sensor systems to detect, measure, quantify, and classify laughter, with their advantages and disadvantages. To this end, we have reviewed studies from different fields in which laughter has been investigated. We individuated the main techniques through which laughter can be detected and measured, monitoring the physical and physiological changes in the body related to laughter production.

Through different methods and for different purposes, the main characteristics of laughter have been isolated and studied, but unfortunately, a comprehensive theory of laughter has not yet been developed. This is becoming of increasingly higher importance nowadays with the advent of intelligent human–machine interfaces, for creating affectively aware technology.

In addition, most of these studies relied on a limited set of samples, due to the elusive nature of laughter and the difficulties in eliciting it under different conditions in a controlled and monitored environment. The development of a multimodal and ecological system to detect and measure laughter would enable a more comprehensive study of laughter for both medical and engineering purposes, allowing a more systematic investigation of the types of features that change under different conditions, both physical (e.g., normal versus pathological) and emotional (e.g. happy versus embarrassed). This is very important given the number of expressive channels involved in laughter production.

This paper has focused mainly on the analysis and description of laughter acoustical features and the physiological and physical changes in the body during laughter production and briefly touched upon the issues of automatic recognition and modeling of this multimodal expression. The analysis of the short- and long-time effects on health that laughter produces on the human body raises very interesting issues and would require significantly more time and space to be addressed and, therefore, have been left for a later publication.

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Sarah Cosentino (M'16) received the M.S. degree in electronic engineering from the Politecnico di Milano Technical University, Milano, Italy, in 2006, and the Ph.D. degree in biomedical engineering at Waseda University, Tokyo, Japan, in 2015.

She is currently a Research Associate at the Faculty of Science and Engineering, Waseda University. During her Ph.D., she was on a MEXT scholarship and was selected in 2014 for the ten-month abroad program for brilliant researchers sponsored by the Japan Society for the Promotion of Science, allowing talented researchers to collaborate with each other in the same or related fields worldwide. Her research interests include human body motion tracking for performance evaluation, skill analysis, training, as well as for humanoid robotics, in particular for natural and artificial emotions and human–robot interaction.

Salvatore Sessa (M'09) received the M.S. and Ph.D. degrees in electronic and control engineering from the University of Catania, Catania, Italy, in 2004 and 2008, respectively.

From 2010 to 2014, he was an Associate Professor at the Department of Mechatronics and Robotics Engineering, E-JUST, Borg El Arab, Egypt, and an Assistant Professor at the Graduate School of Creative Science and Engineering, Waseda University, Tokyo, Japan. He is currently an Assistant Professor at the International Center for Science and Engineering Programs, School of Creative Science and Engineering, Faculty of Science and Engineering, Waseda University. He received royalty for the rights of commercialization of the 9-axis wireless motion sensor e-nuvo IMU-Z, which is based on the design of the WB-3 (Waseda Bioinstrumentation system No.3). His research interests include microelectromechanical system sensors, sensor fusion algorithms, human motion analysis, and mobile robotic navigation and localization.

Dr. Sessa is a Member of the IEEE Engineering in Medicine and Biology Society. In 2009, he received a scholarship by the Japan Society for the Promotion of Science "JSPS Postdoctoral Fellowship for Foreign Researchers" to conduct research in Japan for two years.

Atsuo Takanishi (M'97) received the B.S., M.S., and Ph.D. degrees in mechanical engineering from Waseda University, Tokyo, Japan, in 1980, 1982, and 1988, respectively.

He is currently a Professor at the Department of Modern Mechanical Engineering, Waseda University, and a concurrent Professor and Director of the Humanoid Robotics Institute, Waseda University. His research interests include humanoid robots, such as biped walking humanoid robots, wind instrument player robots, emotion expression humanoid robots, patient simulator humanoid robots, diagnosis robots, and ultra-small inertial motion sensing units.

Dr. Takanishi is a Member of the Robotics Society of Japan (a board member in 1992 and 1993), the Japanese Society of Biomechanisms, the Japanese Society of Mechanical Engineers, the Japanese Society of Instrument and Control Engineers, and the Society of Mastication Systems (a major board member from 1996 to current), and other medicine- and dentistry-related societies in Japan.